NIST Technical Note 1839

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Abstract

The time that it takes an occupant population to reach safety when descending a stair during building evacuations is typically estimated by measureable engineering variables such as stair geometry, speed, stair density, and pre-observation delay. In turn, engineering models of building evacuation use these variables to predict the performance of egress systems for building design, emergency planning, or event reconstruction. As part of a program to better understand occupant movement and behavior during building emergencies, the Engineering Laboratory at the National Institute of Standards and Technology (NIST) has been collecting stair movement data during fire drill evacuations of office and residential buildings. These data collections are intended to provide a better understanding of this principal building egress feature and develop a technical foundation for future codes and standards requirements. NIST has collected fire drill evacuation data in 14 buildings (11 office buildings and 3 residential buildings) ranging from six to 62 stories in height that have included a range of stair widths and occupant densities. A total of more than 22000 individual measurements are included in the data set.

This report provides details of the data collected, an analysis of the data, and examples of the use of the data. The intention is to better understand movement during stair evacuations and provide data to test the predictive capability of building egress models.

While mean movement speeds in the current study of 0.44 m/s ± 0.19 m/s are observed to be quite similar to the range of values in previous studies, mean local movement speeds as occupants traverse down the stairs are seen to vary widely within a given stair, ranging from 0.10 m/s ± 0.008 m/s to 1.7 m/s ± 0.13 m/s. These data provide confirmation of the adequacy of existing literature values typically used for occupant movement speeds and provide updated data for use in egress modeling or other engineering calculations.

Keywords: Disabled, egress, egress modeling, evacuation, fire safety, human behavior, mobility impairments

Executive Summary

The time that it takes an occupant population to reach safety when descending a stair during building evacuations is typically estimated using measureable engineering variables such as stair geometry, speed, stair density, and pre-observation delay. In turn, engineering models of building evacuation use these variables to predict the performance of egress systems for building design, emergency planning, or event reconstruction. As part of a program to better understand occupant movement and behavior during building emergencies, the Engineering Laboratory at the National Institute of Standards and Technology (NIST) has been collecting stair movement data during fire drill evacuations of office and residential buildings. These data collections are intended to provide a better understanding of this principal building egress feature and develop a technical foundation for future codes and standards requirements.

Chapter 2 includes a review of previous studies of occupant movement during building evacuations. At least three key features of these studies influenced the current study. First, much of the literature data is several decades or more old. There has been considerable discussion on the applicability of the older data with the assumption that current populations would be slower than that represented by the older data. Newly-collected data can be compared with historical data partly to assess the applicability of historical data to current building populations. Second, the literature data include only buildings up to 21 stories in height. Taller buildings were of particular interest. The buildings selected for study included a wide range of building heights. Finally, none of the literature studies include data beyond mean values or ranges of values. With more sophisticated egress models under development, this study endeavors to provide detailed data for model development and validation.

This project provides a freely available set of raw data on evacuation-related people movement on stairs in the United States. The data of people movement on stairs consist of the times that each individual is observed by every video camera in every stair in every building observed by NIST (14 buildings total). Within the dataset, 11 of the 14 buildings were office buildings, and 3 buildings were residential. Of the residential buildings, two of the buildings (with a total of 172 evacuees) were exclusively labeled as assisted living facilities or elderly housing, which provided valuable evacuation timing data for people with mobility impairments and elderly occupants. A total of 5244 people (at a total of 173 camera locations) were observed over the 14 NIST-observed buildings, which ranged from 6 to 62 stories in height. A total of more than 22000 individual measurements are included in the data set.

This report provides details of the data collected, an analysis of the data, and examples of the use of the data. The intention is to better understand movement during stair evacuations and provide data to test the predictive capability of building egress models.

Measurements and Data Collection

In this study, data from fire drill evacuations were collected by positioning video cameras out of the way of building occupants to record an overhead view of occupant movement in an exit stair during an evacuation. In most cases, video cameras were placed on specific floors throughout the building to capture a view of that floor's main landing, the door into the stair at that level, and 2-6 steps on each side of the main landing (leading to and from the main landing). This camera placement captured the times in which the occupant was seen moving past a particular floor landing as well as the time when he/she was seen moving into the stairs. Video cameras were placed at least every other floor, sometimes every floor, in each stair, with the exception of Building 6. Since Building 6 was a 62-story building, the number of cameras available for observation made it impossible to place cameras on every other floor in all four stairs. Therefore, cameras were placed nominally every 6 floors throughout each stair. Details of camera placement are available in section 3.1 and Appendix A. Data obtained from the video records included timing of each occupant as he/she entered and left every camera view and additional data such as the occupants location on the stairs and handrail usage. Finally, overall characteristics of the occupants such as gender, body size, floor of origin, whether he/she was carrying anything during evacuation, and whether he/she was assisting or being assisted by someone during the evacuation, were also obtained.

Along with the movement timing, stair geometry including distance travelled on the stairs and landings, stair widths, stair tread depth, stair riser height, and landing size were measured in all of the buildings to allow calculation of delay moving to the stairs for evacuation, stair movement speed, density, and flow.

The data collected and analyzed from these stairs, available on the NIST website at http://www.nist.gov/el/ fire_research/egress.cfm, is a primary output of this research and is intended as a resource for engineers and model developers.

Pre-Observation Delay

Pre-observation delay was defined for each occupant as the time from the initial alarm until the occupant was seen entering the stair to evacuate the building. Across 30 stairs, the mean pre-observation delay of occupants was 230 s ± 53 s. Able-bodied participants had a mean time of 160 s ± 11 s before evacuating into the stairwell. The lowest delays occurred in building 12, with stairwell 12A occupants initiating evacuation after 35 s and 12B after 34 s. The quick pace could be attributed to low overall building population and building height as well as pre-announced evacuations. Stairs with mobility-impaired occupants began to evacuate after a longer period of time, 850 s ± 430 s. These facilities would normally have had higher delays than stairs with able-bodied occupants, having to wait for fire fighter rescue. Evacuees in Building 10, an assisted-living facility, had the longest delay at 1708 s. The extensive delay within the assisted living facility can be explained by the placement of several participants in stair descent devices before evacuation. Firefighters who assisted evacuees often had to spend additional time setting up the device and ensuring that the occupant was safe and comfortable. Section 4.3 discusses pre-observation delay.

Movement Speed

Overall movement speed for each occupant was determined from the total travel distance (from where he/she entered the stair to the exit at the bottom of the stairwell) divided by the difference between entry and exit times. For mean speeds and associated uncertainties, this report uses the harmonic mean which is more appropriate for means that involve averaging travel over different distances. Appendix B includes details of the calculation of mean speeds and their associated uncertainties. Local speeds represent the speeds of evacuees between camera observation points in successive camera views. Section 5.1 discusses occupant speed and density during stair evacuation.

Overall speeds varied from 0.07 m/s to 1.71 m/s with a mean of 0.44 m/s ± 0.19 m/s[1]. The range encompassing observations in this study overlaps with the movement speeds found in previous studies. The mean local speeds varied widely within and among stairs, ranging from 0.10 m/s ± 0.008 m/s to 1.7 m/s ± 0.13 m/s. Individual local movement speeds ranged from 0.06 m/s to 2.8 m/s.

Variable	Sample Size	Mean ± Std. Error	Median
Pre-observation delay time (s)	5249	230 ± 53	170
Overall Speed (m/s)	5244	0.44 ± 0.19	0.47
Peak Density (persons/m^2)	21303	1.87 ± 0.16	2.04

The flow of occupants out the exit door at the bottom of the stairs was seen to be dependent largely on the number of occupants using the stair and the height of the building. The following correlation was found to fit the data with an R^2 of 0.88:

$$F_{ave} = 0.42\left(\frac{P_{total}}{D_{exit}}\right)^{1/3}$$

where F_{ave} is the mean flow out the exit door in persons/s, P_{total} is the total number of people using the stair, and D_{exit} is the maximum distance travelled by people using the stair. This correlation was found to work well for the middle 90 % of those exiting the stairs.

In all stairs, there were a small number of outliers who evacuated early and late in the evacuation. These were estimated to add an average of 22 % to the total evacuation time for a building with a range as high as 61 %. Section 5.3 discusses occupant flow and the impact of early and late evacuees. The table below shows the fraction of the total evacuation time it takes for the early and late evacuees. On average, the early and late evacuees each account for about 20 % of the total stair evacuation time with a wide range for both. Thus, estimation of evacuation time must include an initial pre-evacuation time (time taken by the early evacuees to reach the stairwells), the time taken by the bulk of the evacuees (time taken by the middle 90 % in the analysis in this report), and the added evacuation time for late evacuees. For the latter, a design margin is typically included in the estimates. Section 5.3 discusses occupant flow and the impact of early and late evacuees.

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[1] In this report, uncertainties represent one standard deviation, unless otherwise noted.

Fraction of Total Evacuation Time

	Mean	Range
First 5 %	0.20 ± 0.12	0.03 - 0.46
Last 5 %	0.22 ± 0.18	0.01 - 0.61

Movement Speed for Mobility-Impaired Occupants

Although egress calculations in egress models have been revised to incorporate various behaviors of able-bodied occupants, negligible amounts of egress movement data have been collected for the disabled. Two buildings (Buildings 9 and 10) in the current study were occupied exclusively by older, predominately mobility-impaired adults. Evacuees, whose movements and behavior were analyzed while descending the stairs, included those visually identified as older as well as individuals needing assistance from canes, walkers, stair travel devices, and/or other people (often staff or firefighters).

Occupants evacuated Buildings 9 and 10 at a mean speed of 0.28 m/s ± 0.17 m/s with a range from 0.07 m/s to 0.94 m/s. People assisted by staff members or another occupant evacuated at a mean speed of 0.24 m/s ± 0.13 m/s. Those assisted by firefighters had a mean speed of 0.14 m/s ± 0.05 m/s. Individuals in stair travel devices travelled at a mean speed of 0.20 m/s ± 0.04 m/s. The older population without any disabilities moved faster than the other groups at 0.35 m/s ± 0.17 m/s. In some cases, speeds observed in the current study approximate the speeds of disabled people and older adults found in earlier studies, and in other cases were slower than previous studies. Slower speeds may have resulted from observing a wider variety of mobility impairments (because one of the observed buildings was an assisted-living facility). In addition, the assistance to evacuees provided by untrained populations on the use of the stair descent devices, rather than trained populations. Section 5.2 details the evacuation of mobility-impaired occupants in the current study.

Parameters That Influence Occupant Movement

From regression modeling and Bayesian analysis of both the flow correlations (see section 5.3) and point process modeling (see section 5.4), the two most significant variables were the number of occupants using the stairs and the height of the building, with a clear regression between these variables and flow out the stairs at the exit door.

Surprisingly, stair width did not have a statistically significant impact on occupant flow. Some of this may be simply because typical building design calls for increased stair capacity (typically by increased stair width) as floor population in the building increases. Another possible explanation for the contradiction in findings (on the effect of stair effective width) is the lack of variance in effective width among NIST-observed building samples. All of the buildings observed in this study were code-compliant buildings with effective stair widths ranging from 756 mm (29.75 in) to 1232 mm (48.5 in), with the majority (62 %) of stairs falling within the narrow range of 729 mm (28.7 in) to 813 mm (32 in).

Additional observation of tall buildings in the United States and experimentation in a laboratory setting of evacuations using a wider range of stair widths would be needed to increase the strength of the findings in this report and potentially provide concrete evidence of the benefits (or lack thereof) of incremental increases in stair widths.

Techniques for Improved Egress modeling

In addition to providing additional data on occupant movement in stair egress, the report also included more detailed analysis of path selection and clustering.

A detailed analysis of some of the data (see section 5.5) showed that both variation of movement speeds and path selection can be successfully described with a single parameter distribution for a base path.

Sample comparisons of the data to an existing egress model (see section 5.6) demonstrate the usefulness of the data for model validation. These comparisons show that the level of detail in the model inputs can have a significant impact on the quality of the predictions. Additional analysis of the data would help better define the necessary range of inputs and their appropriate use in a range of egress models.

Point process modeling was seen as a promising technique to quantitatively account for clustering of occupants during stair egress. Use of the Hawke's point process model (see section 5.4) showed a consistent measure of clustering in all of the stairs, regardless of crowding, stair width, door placement, etc. Additional study would be required to better understand its applicability to egress modeling.

Additional Research Needs

This report provides just a beginning in understanding the additional human behavior-related factors that impact movement beyond classic hydraulic calculation-based variables. Additional research is needed to better understand these factors, including the following:

- To fully understand overall exit times for building egress, a better understanding of movement and behavior of occupants prior to entering the stairs is required. This report presented a simple analysis of the time occupants take to arrive at the stair for egress. No data was collected in this study of occupant movements prior to entering the stairs.
- Additional data on movement speeds, particularly in taller buildings and with various stair widths are needed to better understand the important variables that impact stair movement speeds.
- Additional analysis of stair movement data to determine the best values and distributions for egress model inputs would facilitate modeling and help understand additional data needs through use of the data.
- Additional analysis of stair movement data using the Hawke's point process model would help clarify clustering in stair movement and its impact on occupant flow.
- Further analysis is needed to fully understand whether fatigue occurs during building evacuations, and if so, the factors that impact fatigue, including distance traveled, age,

physical ability, fitness level, etc. Additionally, if fatigue is present in certain conditions during building evacuations, it will be important to understand its impact on occupant movement speeds and flow.

- Additional analysis of merging behavior is needed, including an understanding of the proportion of stair users versus occupants entering the stairs for a variety of building scenarios (i.e., building type, occupant type, scenario type, etc.).
- Analysis of the evacuation timing of stairs versus elevators is needed, including the benefits of evacuation via elevators for different types and heights of buildings.
- Data collection and analysis of behavioral data before and during stair evacuation as well as elevator evacuation is needed. This includes additional information on the movement of occupants with mobility impairments on stairs and other building egress components.
- Since all of the analyses in this report are based on fire drill evacuations, additional research on the similarities or differences between these evacuations and real fire emergencies is needed to place the results in context.

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1 Introduction

Science-based egress designs and evacuation procedures have significant potential to mitigate the growing costs of fire protection features in building construction, which are now approximately $63 billion annually in the United States [1]. Adoption and appropriate use of efficient egress designs and advanced egress technologies can provide safer and more cost effective building designs, particularly for taller buildings.

The tragic loss of life in the 2001 World Trade Center attacks sheds light on the levels of safety provided by tall buildings in the United States, and the technical foundation of the mechanisms used to provide or assess these levels of fire safety: U.S.-based prescriptive and performance-based codes and standards. In prescriptive codes, building egress systems are designed around outdated stair capacity concepts in the building codes and standards or numerical egress models where the limited amount of usable input or validation data renders output highly uncertain. Economical building designs, changing occupant demographics, and consumer demand for more efficient systems have driven egress designs beyond the traditional stair-based approaches, with little technical foundation for performance or consideration of economic trade-offs.

Similarly, performance-based analysis of building egress is based upon the use of analytical tools and models that may be sophisticated in design but built upon datasets extremely limited in number, size, scope, and representativeness. Current egress techniques even go so far as to develop capabilities not technically founded in research and data, and/or require the users to supply data as input for egress-related areas where little or no data exist. Additionally, while some models have been subjected to extensive verification and validation efforts, as well as uncertainty analyses [2], many have not.

This report focuses on the understanding of evacuation movement of people in stairs. While real emergency data is most desirable and might provide the most realistic predictor of behavior, it is not as readily available as fire drill data. For practical purposes, fire drill data is often used to represent emergency behavior. A key assumption, consistent with most of the data presented in the literature values discussed in Chapter 2, is that fire drill data can be used to approximate the response of individuals in an actual emergency [3]. This is, of course, dependent on whether the population is directly exposed to smoke and/or fire cues; meaning that fire drill data may best approximate the reaction and conditions experienced of those who are not close enough to the hazard to identify it as an emergency. In many high-rise evacuations, as is the case in this study, it is also conceivable that a significant portion of the population has not been exposed to enough fire cues to be certain if it is an emergency.

Therefore, the majority of the report focuses the provision of data on the speed or rate of descent of occupants on stairs during fire-drill evacuations, and the identification of the building-related factors that most influence evacuation rates (and in turn, evacuation efficiency) on stairs in tall buildings. Intended to complement earlier research on the use of elevators for occupant evacuation [4], this report provides technical foundation for best practices in the design and evaluation of safety provided by egress systems for tall buildings in the U.S.

Although the primary focus of this report is on stair evacuation movement speed and the important stair design parameters that may impact this movement, human behavior also plays a key role in the overall evacuation timing. Thus, information on the timing prior to occupants entering the stair is included. Additional analysis of behavior is not included in this report, though some analysis of data collected from questionnaires is available in reference [5].

1.1 Purpose

As part of a program to better understand occupant movement during building emergencies, the Engineering Laboratory at the National Institute of Standards and Technology (NIST) has been collecting stair movement data during fire drill evacuations of office and residential buildings. These data are intended to provide a better understanding of principal building egress features and develop a technical foundation for codes and standards requirements as well as egress modeling techniques. To date, NIST has collected fire drill evacuation data in 14 buildings ranging from six to 62 stories in height that include both office and residential occupancies, and a range of stair widths and occupant densities.

This report provides details of the data collected, an analysis of the data, and examples of the use of the data. The intention is to better understand movement during stair evacuations and to test the predictive capability of building egress models.

1.2 Report Organization

This report is organized as follows.

- Chapter 2 reviews building code requirements and previous research results related to stair egress.
- Chapter 3 describes the data collected and techniques used for the collection of the data.
- Chapter 4 presents the results including the time occupants took to move to the stairs, movement speed in the stairs, and occupant density observed on landings in the stairs.

- Chapter 5 includes an analysis of the data to identify important parameters that influence the speed of stair evacuation and provides examples of the use of the data to better understand human behavior and modeling of stair egress.

- Chapter 6 summarizes the important findings from the research and outlines important areas for future research that were not addressed in the current study. Implications of the results on both building code requirements and engineering analysis are discussed.

- Finally, the appendices provide additional details for several topics in the report.

    - Appendix A details measurements of all of the stairs included in the study (referenced in Section 3.4).
    - Appendix B describes the calculation of harmonic mean and uncertainties for movements speed data included in the report (referenced in Sections 4.1.4 and 4.4).
    - Appendix C presents local movement speeds at every camera location in all the stairs included in the study (referenced in Section 4.4.2).
    - Appendix D includes details of the linear least squares and Bayesian analyses used to determine important parameters that impact occupant movement in stairs (referenced in Section 5.3).
    - Appendix E reviews the underlying theory of point process modeling (referenced in Section 5.4).

2 Background and Previous Research

This section provides an overview of research related to stair evacuation, including movement speeds and flows, occupant densities in stairs, and, to a lesser extent, behavior of occupants prior to and during building evacuation using stairs. This section ends with a review of the current building codes and standards used to design egress systems for tall buildings and the current egress models (i.e., simulation techniques) used to assess the safety provided by a building design in a performance-based analysis.

Before research related to stair evacuation is provided in this section, a brief overview of the main phases of an individual's building evacuation is presented, as shown Figure 1. An evacuation comprises both the pre-evacuation period and a movement period. The pre-evacuation period consists of the time from when an occupant realizes that something is wrong and ends when the occupant begins to travel an evacuation route out of the building, whereas the movement period consists of the time taken to travel an evacuation route out of the building until safety is reached.

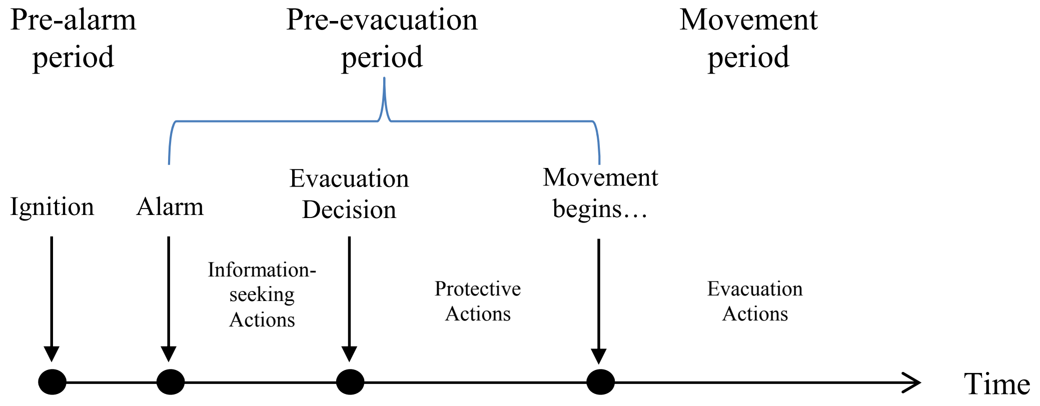

Figure 1. Major components of a building evacuation.

During a building fire, the event begins with ignition somewhere in the building, or a location that could cause harm to occupants located in a building. This is denoted in Figure 1 with a black dot at the beginning of the evacuation timeline. The next phase pictured in Figure 1 is that of the pre-alarm period, or the time period between ignition and when the fire alarm (or other signaling means, including a person detecting a fire and beginning to alert others in the building of the event) is activated in the building. The pre-alarm phase can be very quick if a fire is detected soon after ignition, or could be a lengthy process in which only building staff are made aware of an event, for example, and take time to investigate before making the larger building population aware of the event. The next phase in the pre-evacuation period involves information seeking and the receipt of cues, which itself involves movement, interactions with others, and is iterative, eventually leading to the decision to evacuate (especially if sufficient information is received, leading to the perception of personal risk). As shown in Figure 1, once occupants decide to evacuate, the next phase in the pre-evacuation period is the performance of protective actions. In a building fire, protective actions can consist of gathering personal items, assisting others, alerting others of the need to evacuate, and/or firefighting. Once protective actions are performed (if any at all), occupants transition into the movement period of the building evacuation, consisting of using egress paths in the building to reach safety.

Since much of this report provides data on pre-evacuation delay time and stair movement (see Chapter 4 of this report), the following two sections, 2.1 and 2.2, provide data from previous studies on these topics, respectively. Subsequently, sections 2.3 and 2.4 provide an overview of the current status of egress-related prescriptive and egress modeling techniques that may or may not use these data to assess building safety.

2.1 Earlier Studies on Pre-evacuation Timing/Delays and Behavior

Researchers have studied the time delay from initial notification of a fire event to the beginning of evacuation, often termed "pre-evacuation time," but more accurately described as evacuation initiation delay. This type of information is often captured via observation (e.g., videos) and/or post-event surveys or interviews, and attempts to determine the range of delay time, including mean and standard deviation, for a specific building evacuation event. This section provides a literature review of pre-evacuation studies from a variety of building types and events, including fire drills and actual fire emergencies. Each study will be briefly described before presenting pre-evacuation timing data, and will list explanations of delay, if provided in the original research article. This section will conclude with all pre-evacuation delay data presented in tabular form (see Table 1 on page 10).

2.1.1 Real Fire Incidents

The following studies collected data on pre-evacuation delay times from occupants who were in buildings where actual fire incidents occurred. First, Bryan studied occupant behavior during the MGM Grand Hotel fire in Clark County, Nevada [6]. He sent out questionnaires to the hotel guests who were registered at the time of the incident. The questionnaire was intended to gauge occupant interaction and behavior throughout the evacuation process. When the fire broke out, no alarm warning was sounded to alert occupants of the pending danger. Findings show that the average pre-evacuation delay time for 536 persons was 60 seconds.

Fahy and Proulx compiled findings on human behavior during emergency evacuations after a bomb was detonated in an underground parking garage at the World Trade Center in New York City in 1993 [7]. Occupants of the surrounding buildings were required to follow specific fire safety procedures that included a minimum of two fire drills each year. The impact of such training prior to this emergency was given particular attention when analyzing the occupant behavior data collected from the investigation of this explosion. An account of individual behavior was obtained from the 419 completed surveys submitted from occupants in the two towers. They report pre-evacuation delay times for the 229 occupants in Tower 1 ranged from 2 minutes to 30 minutes with a mean time of 8 minutes and 54 seconds while the pre-evacuation delay times for the 163 occupants in Tower 2 ranged from 5 minutes to 240 minutes with a mean time of 39 minutes and 54 seconds. Occupants from Tower 1 reported shorter delay time periods than occupants in Tower 2 and accounts of calling family or friends before evacuating was reported more frequently among occupants in Tower 2 than those in Tower 1. Fahy and Proulx suggest that this was due to fewer clear warning cues received by occupants in Tower 2 since the location of the explosion was closer to Tower 1.

Taking a new approach to quantifying pre-evacuation delay times, Brennan (1997) conducted interviews with 36 participants who evacuated a 14-story office building after a fire broke out on the third floor [8]. Participants gave an informal description of their experiences before researchers questioned the rationale behind each action that was mentioned. Specific times indicating when the pre-evacuation delay times ended and the evacuation stages began were retrieved from outside sources to ensure that the data collected was not biased by participants' misconceptions of their experiences. Brennan reports that pre-evacuation delay times ranged from 60 to 300 seconds.

Averill et al. [9-12], as part of the NIST Federal Investigation of the World Trade Center (WTC) disaster in New York City in 2001, collected data on pre-evacuation delays from survivors of the two towers (WTC 1 and WTC 2). A total of 803 telephone interviews were performed, asking survivors about their emergency training and preparedness, the three stages of the evacuation experiences (the first moments when WTC 1 was attacked, the interim period between initial awareness and entering a stair/elevator, and the time spent in the stair or elevator), and background information about the respondent. Data collected during the interim period of the evacuation provided insight on the time occupants spent in both buildings before beginning evacuation (defined as the time interval from first awareness to the time the respondent left his/her floor to begin evacuation). In WTC 1, on average, survivors began their evacuation within 6 minutes. Similarly, survivors of WTC 2 began their evacuation also within 6 minutes, on average. Looking into the data a bit further, the most frequent response for survivors throughout WTC 1 and 2 was one minute or less, and 50 % of the occupants had left their floors within 3 to 5 minutes (depending on the three evacuation zones; basement to floor 42, floors 43-76, and floors 77-91). However, a few individuals in the towers took significantly longer (sometimes longer than 30 minutes) to begin evacuation, which disproportionately affected the mean start time for WTC 1 and 2. Averill et al. (2005) provides further data on the quartile, mode and average times to start evacuation for survivors of both towers, categorized by zones within each tower.

2.1.2 Evacuation Studies

Proulx et al. observed evacuation drills from seven mid-rise and high-rise residential buildings in Canada [13, 14][2]. Although occupants were given advanced notification that a fire drill would be conducted in the building, no information regarding when the drill would take place was disclosed. The video cameras that were set up in the hallways of each building were used to document the pre-evacuation delay times for over 500 occupants. After the evacuation was completed, approximately 25 percent of the residents reported the belief that there was a real fire

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[2] In one of the buildings, occupants evacuated onto their balconies instead of proceeding to the ground floor and exiting the building. Although times that occupants appeared on their respective balconies were recorded, data on occupants' pre-evacuation delay times from this building are too obscure and therefore are not included here.

in the building and that the alarm was not a drill. The average pre-evacuation time for occupants in the six buildings ranged from 169 s to 540 s. To explain the differences in the observed delay times, researchers note that the audibility of the alarm system in one of the buildings was very poor. As a result, many occupants did not prepare to evacuate until they heard the sirens of approaching fire trucks or until they received warnings from firefighters knocking on their doors. The researchers also point out that the drills done in the three buildings with the shorter observed mean delay times were each performed during the summer in the evening on a weekday while the drill done in the building with the longest mean delay time took place on a Saturday morning in the winter. Proulx and colleagues suggest that the cold weather outside caused longer delay times because residents took extra time to put on coats, boots, etc. before evacuating.

In order to assess and optimize the effectiveness of photoluminsecent material in evacuations during a blackout, Proulx and Bénichou conducted evacuation drills in a 13-story office building in Canada [15, 16]. Pre-evacuation delay times of 1191 occupants were recorded by video cameras with a mean time of 329 seconds.

Gwynne observed multiple evacuation drills in various buildings and quantified occupants' evacuation times [17]. These drills were activated by different emergency notification systems in order to evaluate which system produced the most rapid response. Two of the buildings observed in his study were multi-story office buildings located in the UK, one had 11-stories and one had 4-stories. The drill in the taller building used an alarm with voice, tone and strobe capabilities, compared to a notification system with only tone and strobe alerts that was used in the low-rise building. Gwynne mentions a few more inconsistencies between the buildings. For instance, fire drills had been conducted in the 4-story office building within the previous year and rarely had a false alarm, whereas no such drills were conducted in the 11-story office building and false alarms were triggered relatively frequently. Drills in both of these buildings were observed during inclement weather[3] and pre-evacuation delay times were collected from video recordings, supported by documentation from human observers and occupants' responses to surveys. Individual pre-evacuation delay times for 72 observed occupants in the 11-story building ranged from 40 to 426 seconds with a mean delay time of 2 minutes and 21.3 seconds. Pre-evacuation delay times for the 348 observed occupants in the 4-story building ranged from 19 to 269 s with a mean time of 101 s.

Purser and Raggio studied response to voice notification and sound alarms in building evacuations [18]. In one study, video cameras were used to record the pre-evacuation behavior of 12 visiting occupants in a meeting room on the 3rd floor of an office building in the UK. The alarm emitted a four-second warning signal followed by a voice message lasting 13-seconds. Quickly responding to the alarm, occupants were recorded gathering their belongings and exiting the building. Computed from the raw data, pre-evacuation delay times were found to be relatively short, ranging from 32 to 57 seconds with a mean time of 46 seconds.

Gwynne and Boswell conducted a study to examine pre-evacuation delay times in a mid-rise administrative building [19]. Video cameras and human observers were strategically situated to document pre-evacuation behavior without inadvertently revealing their objective to building

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[3] For the 11-story building, the weather conditions were reported as "very cold; presence of snow and ice." For the 4-story building, the weather conditions were reported as "cold, but clear."

occupants. Data extracted from video cameras for 132 occupants show pre-evacuation delay times ranged from 23 to 152 seconds with a mean time of 74 seconds; manual documentation of pre-evacuation delay time for 150 occupants ranged from 5 to 173 seconds.

Sharma et. al., in order to create new egress modeling software, collected data on occupant behavior evacuating from a 6-story office building in the UK [20]. By way of video cameras and surveys, the individual pre-evacuation delay times for the 19 observed occupants ranged from 10 to 55 seconds with a mean time of 28 seconds and a standard deviation of 11 seconds.

Many buildings mandate resident or employee participation in fire safety drills or training courses to ensure that occupants know where to go in the event of an emergency. Researchers have commented on how previous training may affect occupant behavior during emergency evacuations. In one study, Proulx and Pineau documented the pre-evacuation delay times for over 1000 occupants within three Canadian office buildings [21]. Although occupants had received evacuation training, researchers pointed out that the employees often completed whatever tasks they were working on before proceeding to evacuate. These occupants averaged a 50 second delay time which was considerably shorter than the observed movement in Proulx's studies on occupants in residential buildings [13, 14].

Shields, Boyce, and Silcock examined evacuation behaviors of customers in retail stores [22]. This study implemented video cameras to monitor customer behavior. With a mean pre-evacuation delay time of 25 seconds, Shields, Boyce and Silcock observed that the amount of time that lapsed before customers began evacuating depended heavily on the staff's response and compliance with emergency procedures.

Shields and Boyce observed this same relationship between staff and customer evacuation behavior when they conducted unannounced evacuation drills from four Marks and Spencer stores in the UK [23]. Video cameras were used to monitor customer behavior in each store. Pre-evacuation delay times for the four buildings recorded from this study are as follows: 122 customers were observed in two store locations, 95 in the third location and 71 in the fourth location with respective mean pre-evacuation delay times of 37 s ± 19 s, 31 s ± 18 s, 25 s ± 14 s, and 25 s ± 13 s.

Finally, Christoffersen and Söderlind conducted an unannounced fire drill in a 12-story office building in Copenhagen [24]. Interested in the efficiency of egress models from tall buildings, video cameras were set up in stairs on every other floor and human observers were stationed on each floor to document occupant timing. Pre-evacuation delay times ranged from 12 to 105 seconds. These findings account for only 70 occupants as reported from observers on 3 of the floors. Christoffersen and Söderlind also note that building policy required biannual fire drills so employees were accustomed to such procedures and were relatively quick to respond.

Table 1 includes a summary of the studies of pre-evacuation time during building evacuations. Description of the building location, occupancy, and height along with details on the type of evacuation (actual incident, informed, or uninformed drill), type of alarm notification, and data collection method. Finally, a summary of the results of the studies are included. These results vary depending on the type of reported results and may include mean values, median values, or the range of observed pre-evacuation times. Additional notes on the study are also included.

Table 1. Summary of pre-evacuation time literature

Source[a]	Building Description[b]	Drill Method	Alarm Type	Data Collection Method	Sample Size	Pre-evacuation Time[c]	Notes
Bryan 1983	L: USA T: Hotel F: 23	N/A	No alarm notification	Post-incident surveys	536	R: 0-290 Median: 60s	
Fahy and Proulx 1997	L: USA T: Office Tower 1 F: 110	N/A		Post-incident surveys	229	M: 534 R: 120-1800	-Suggest that shorter delay times observed in Tower 1 are due to clearer emergency cues since Tower 1 was closer to the explosion.
	L: USA T: Office Tower 2 F: 110				163	M: 2394 R: 600-14414	
Brennan 1997	L: Australia T: Office Building F: 14	N/A	No alarm notification	Fire brigades and other documented sources	36	R: 60-300	
Averill, et. al. 2005	L: USA T: Office Tower 1 F: 110	N/A		Post-incident telephone interviews	803	M: 300 R: 60-1800+	-Average delay time 6 minutes in each tower, majority of occupants initiated evacuation prior to 6 minutes, but a small number with much larger delay times skewed the data.
	L: USA T: Office Tower 2 F: 110					M: 300 R: 60-1800+	
Proulx, et. al. 1994 1995	Buildings 1-3 L: Canada T: 3 Residential Buildings	Quasi-Informed	Good audible quality	Video cameras	>500 total	M: 169	-Summertime
	Building 4 L: Canada T: Residential Building		Good audible quality			M: 319	-Wintertime, suggested explanation for longer observed delay times than those in buildings 1-3
	Buildings 5 - 6 L: Canada T: 2 Residential Buildings		Poor audible quality			M: 540 R: 120-1500	-Summertime -Suggests that long delay times are a result of poor audible alarm quality

Table 1. Summary of pre-evacuation time literature, continued

Source[a]	**Building Description[b]**	**Drill Method**	**Alarm Type**	**Data Collection Method**	**Sample Size**	**Pre-evacuation Time[c]**	**Notes**
Proulx and Bénichou 2008	L: Canada T: Office Building F: 13	Uninformed	Fire alarm bell rang for 11 minutes and 51 seconds	Video cameras	1191	M: 329	-Wintertime -Occupants got dressed (coat, gloves, etc.), gathered valuables, secured files
Gwynne 2007	Building 1 L: UK T: Office Building F: 11	Uninformed	Voice/tone/ strobe	Video camera, observers, post-incident surveys	72	M: 141.3 R: 40-426	-Wintertime
	Building 2 L: UK T: Office Building F: 4		T-3 Notification System (tone and strobe)		348	M: 101 R: 19-269	
Purser and Raggio 1995 Purser and Bensilum 2001	L: UK T: Single meeting room on 3rd floor of large office building	Uninformed	Alarm had a 4-second sounder warning signal followed by a 13-second voice message	Video cameras	12	M: 46 R: 32-57	-Occupants collected belongings
Gwynne and Boswell 2009	L: North America T: Office Building F: mid-rise	Uninformed	Alarm had 3 slow whooping sounds followed by a voice message. Three minutes later, a general alarm was sounded	Video cameras, observers	132	M: 74 R: 23-152	
					150	R: 5-173	
Sharma, et. al. 2009	L: UK T: Office Building F: 6	Uninformed		Video cameras, post-incident surveys	19	M: 28 ± 11 R: 10-55	

Table 1. Summary of pre-evacuation time literature, continued

Source[a]	Building Description[b]	Drill Method	Alarm Type	Data Collection Method	Sample Size	Pre-evacuation Time[c]	Notes
Proulx and Pineau 1996	L: Canada T: 3 Office Buildings	Uninformed		Video cameras	>1000	M: 50	-Occupants had previous training and had annual fire drills -Occupants typically completed activities before responding
Shields, Boyce and Sicock 1998	T: Retail Store F: 1	Uninformed		Video cameras		M: 25 Maximum: 55s	-Customer response depended on staff behaviour / response
Shields and Boyce 2000	Building 1 L: UK T: Retail Store F: 3	Uninformed		Video cameras	122	M: 37 ± 19 R: 3-95	-Customer response depended on staff behaviour / response
	Building 2 L: UK T: Retail Store F: 3				122	M: 31 ± 18 R: 4-100	
	Building 3 L: UK T: Retail Store F: 1				95	M: 25 ± 14 R: 1-55	
	Building 4 L: UK T: Retail Store F: 1				71	M: 25 ± 13 R: 2-60	
Christoffersen and Söderlind 2009	L: Denmark T: Office Building F: 12 floors	Uninformed		Video cameras, observers	70	R: 12-105	-Biannual fire drills

a – Author and year

b – L = location, T = building type, F = number of floors

c – M = mean seconds, SD = standard Deviation in seconds, R = range in seconds

After the pre-evacuation period, the next phase in the building evacuation timeline is the movement period. A compilation of studies reporting data collected from the movement period are provided in the following section.

2.2 Earlier Studies on Stair Movement

Researchers have also studied and collected evacuation time from a variety of buildings under different emergency and non-emergency conditions. In order to calculate evacuation time of a particular building, researchers have collected three different types of people movement data during evacuation. The most common type of data is movement speed. Movement speed has been reported both in terms of distance per unit time (e.g. m/s) as well as in terms of the number of floors per unit time (or unit time per floor). Multiple researchers have developed correlations to calculate the speeds of evacuees based upon specific independent variables. The most common independent variable in those equations, density, is a second type of data that researchers have collected. Density has typically been reported in terms of persons per unit area (e.g. persons/m^2), but it has also been given as a dimensionless ratio of the area occupied by persons per the floor area. The third type of data that has been collected is the flow of occupants through various building components. Occupant flow is measured as the number of people past a certain point in the building component, often times a point on the stairs or at a doorway, per unit time (i.e., people per second). Additionally, for comparison purposes, flow is sometimes reported as the number of people past a point in the building, per unit time per unit width of the component (referred to as specific flow).

Data on speed, density and flow have been organized in the sections, below. Data collected from actual fire events will be presented first, followed by data from evacuation drills, normal conditions, and then laboratory experiments. Finally, this is then summarized in Table 2 (following the text).

2.2.1 Actual Fires

Averill et al. [9] conducted telephone interviews with survivors of the World Trade Center collapse in New York City in 2001 (n=803). A certain sample of these interviewees (n=368, occupants of floor 10 to floor 91 in WTC 1) reported time spent in the stairs and thus, their stair speeds during evacuation were analyzed in the study. In Tower 1 (two stairs 1100 mm-wide stairs and one 1400 mm-wide stair), the average movement speed was 0.2 m/s for the entire evacuation via stairs. This included any rest periods, crowding in the stairs, transfer floors, switching stairwells, and the impact of smoke, water, and a significant number of obstacles in the stairs reported by many occupants [9].

Shields, Boyce, and McConnell [25] used data collected from interviews from six survivors of the 2001 World Trade Center collapse that had self-identified mobility impairments prior to September 11, 2001. For five of the six occupants, the authors were able to describe the activities and movement speeds (in terms of floors) as they descended. These speeds ranged from 43 s/floor to 150 s/floor.

As part of their study, Galea et al. [26] interviewed survivors of the 2001 World Trade Center collapse (129 from Tower 1 and 125 from Tower 2). From the accounts of thirty interviewees from Tower 1, the average speed was 0.29 m/s.

2.2.2 Fire Drills

Pauls [27] observed a pre-event announced drill in a commercial building in Canada, which had 910 occupants using two 1190 mm stairs with 178 mm riser heights and 254 mm tread depths. An additional 35 occupants who could not walk down the stairs were able to use elevators for egress. Observers moved within the main flow and the author was able to estimate the average descending speed of evacuees. These values ranged from 0.61 m/s to 0.81 m/s.

Pauls and Jones [28] studied two office building evacuations with unannounced evacuations in Canada. For the first evacuation, there were five 1140 mm-wide stairs. A total of 1453 able-bodied people used four of the five stairs and 73 people who were disabled or assisting the disabled occupants used the center stair. Above the seventh floor, the movement speeds along the slope of the stairs were lower than below the seventh floor due to the stairs being used at a significantly greater density, with the slowest recorded speed being 0.23 m/s. Below the seventh floor, the average speed was 0.44 m/s. On the ground floor, the mean speed was 0.66 m/s with a mean density of 1.38 persons/m^2. In the second building, the authors did not provide movement speeds.

Proulx [29] videotaped fire drills in four similar apartment buildings in four different Canadian cities. All of the buildings were 6 to 7 stories high. The average speed on the stairs ranged from 0.52 m/s to 0.62 m/s. Children between the ages of 2 to 5 years old and the elderly had average speeds of 0.45 m/s and 0.43 m/s, respectively. During the evacuations, occupants tended to use stairs that they used on a regular basis even if other stairs were closer to their apartment. The stairs were never crowded during the drill (although the density was not reported), but many occupants traveled in groups.

Proulx, et al. [14] recorded evacuations from three high-rise buildings in Canada. For all of the drills, cameras were placed in corridors as well as in both stairs (each building had exactly two). Occupants tended to travel in groups and use the nearest stair. The groups were described to be moving at the speed of the slowest member and the stairs were described as not being crowded. For the first building in the Proulx et al. study [14], the average speed on stairs was 1.07 m/s. Fourteen men averaged 1.14 m/s and fifteen women averaged 1.00 m/s, but the difference was not significant. Groups traveled slightly slower than individuals (nineteen group members averaged 1.00 m/s while ten individuals averaged 1.18 m/s). The second building had an overall average speed on stairs of 1.05 m/s (n=28 occupants). Women moved slightly faster, but again, the difference was not significant. For the third building, the average speed for 76 occupants was 0.95 m/s. For descending stairs, men moved statistically faster (1.05 m/s) than women (0.86 m/s). The authors then compared the descent speeds of each gender across the three buildings. Neither the descent speed of men nor women was significant across the three buildings. The authors then combined the populations from the three buildings and found that men (average speed 1.07 m/s) and women (average speed 0.90 m/s) were not statistically significant at the 95% confidence level.

Proulx, Kaufman, and Pineau [30] observed evacuation drills in two government office buildings in Canada. Video cameras were located in corridors and in the stairs. There were 165 occupants in the first building, descending the stairs at a mean speed for all occupants of 0.78 m/s. Additionally, women traveled statistically faster than men (0.81 m/s compared to 0.72 m/s). The second building had 502 occupants. The average speed on the stairs was 0.93 m/s. Men had a statistically faster average speed (0.96 m/s) than women (0.90 m/s).

Shields, et al. [31] observed an unannounced drill in an educational building in the UK with 276 occupants present. Two stairs were located within the building with 77% of the population using one stair. People descending behind a wheelchair had a mean movement speed of 0.33 m/s and those ahead of the wheelchair had average speeds of 1.1 m/s.

Proulx, et al. [32] recorded people movement data from 457 occupants in four stairs during a building evacuation drill in Canada. Each stair was equipped with different illumination levels. In the stair with only the photoluminescent markings, 144 occupants had a mean speed of 0.57 m/s with a range of speeds from 0.39 m/s to 1.13 m/s. There were 65 occupants in the stair with reduced emergency lighting and photoluminescent markings who had speeds from 0.64 m/s to 1.30 m/s (average 0.72 m/s). For the stair with only reduced emergency lighting, 82 occupants had speeds from 0.41 m/s to 1.14 m/s and a mean speed of 0.70 m/s. In the control stair with normal emergency lighting, there were 101 occupants whose speeds varied between 0.45 m/s to 0.84 m/s with a mean speed of 0.61 m/s. Density was calculated for the average conditions in each stair during the busiest three minutes of the drill. The densities were 2.05 persons/m^2 (photoluminescent markings stair), 1.00 persons/m^2 (reduced emergency lighting and photoluminescent markings stair), 1.23 persons/m^2 (reduced emergency lighting stair), and 1.30 persons/m^2 (normal emergency lighting stair).

Khisty [33] observed 21 unannounced fire drills and normal use in dormitories 3 to 12 stories in height in Washington State. Drills were conducted at all hours of the day with the latest one at 11 p.m. Exit interviews with a random sample of at least 10% of the occupants after each drill found that 80% of occupants thought that the drills were real incidents. Across all buildings, the stair risers varied from 165 mm to 190 mm with tread heights from 279 mm to 305 mm. The width of the stairs varied from 1220 mm to 2130 mm. Time-lapse photography at 18 frames per second was used to record the drills. Observers also moved within the flow to collect data. During the emergency evacuation, the mode and median of density were 1.96 persons/m^2 and 1.40 persons/m^2, respectively. Comparatively, under normal conditions, the mode and median of density were 1.66 persons/m^2 and 1.38 persons/m^2, respectively. The highest recorded speeds were 0.64 m/s and 0.70 m/s for normal and emergency conditions respectively. Flows were also seen to increase under emergency conditions. The maximum specific flow increased from 0.90 persons/m-s to 1.00 persons/m-s.

Proulx, et al. [16] observed a single fire drill in Canada with approximately 4000 occupants. Of the 4000 occupants, 1191 occupants were recorded in the studied stairs. Four of the six 1100 mm stairs in the building were observed during the drill. All of the stairs had densities that ranged from 1.56 persons/m^2 to 1.60 persons/m^2 during the busiest five minutes of the drill and the maximum density was 2.30 persons/m^2. The speeds for occupant descent ranged from 0.17

m/s to 1.87 m/s. The mean speed in four stairs was 0.40 m/s, 0.57 m/s, 0.66 m/s, and 0.66 m/s. The slower speed in one of the stairs was attributed to the descent of individuals with mobility impairments.

Hostikka, et al. [34] observed the evacuation of 281 occupants from a 7-story office building in FInland. There were four egress paths usually available, but two of the more commonly used exits were blocked using cold smoke. Occupants were observed using both video cameras and radio frequency identification (RFID) tags. Queues formed under two different scenarios. First, slower individuals moved to the side to let people from higher floors pass them. Second, one group stopped to let occupants from lower levels enter the stair. From video images, the flow rates on the lower floors ranged from 0.80 persons/m-s to 0.83 persons/m-s. For densities less than 0.5 persons/m^2, the data was scattered with most observations falling between 0.5 m/s to 1.5 m/s. For densities between 0.5 persons/m^2 to 2.5 persons/m^2, the velocity decreased linearly from approximately 0.75 m/s to 0.5 m/s. The median value was 0.64 m/s. Men and women were found to travel at the same speeds.

From the late 1960s to the 1970s, Pauls [35] conducted 58 total evacuations from high-rise office buildings in Canada. The stairs had widths that ranged from 910 m to 1520 mm. The variation of riser heights and tread dimensions were not provided, but mention was made of the maximum tread depth, 279 mm, and at least one stair with a tread depth of 229 mm. Also, the exact heights of buildings were not given, but buildings 18 to 20 stories were described as being very tall. Regarding people movement, Pauls found that disabled occupants slowed the flow in their general vicinity, but had no noticeable effect on the overall flow. Also, Pauls identified 20 of the 58 cases as being ones where individuals required coats due to cold or wet weather. In these cold or wet weather evacuations, the flows dropped by 6 %. Furthermore, Pauls concluded that the optimum evacuation conditions (maximum flow) occurred when the density was 2.0 p/m^2 for which the speed was 0.5 m/s.

Kagawa, Kose, and Morishita [36] video recorded a fire drill in a 53 story high-rise office building in Japan. Approximately 1500 individuals used two 1.20 m-wide emergency stairs. Generally speaking, observers had an initial delay after first entering the stairs and then descended approximately one story every 16 seconds. Stagnation of the flow was reported in several locations, but the density did not exceed 3 persons/m^2.

2.2.3 Normal Conditions

The movement of people under normal conditions was also collected and related to evacuation during fires. Examples include people moving through mass transportation stations or leaving a theater after the performed has ended.

Fruin [37], as part of his work on pedestrian planning, observed people on two stairs on the East Coast of the United States. On an indoor stair with a 178 mm riser and 286 mm tread, descent speeds on stairs were the following:

- Men under 30 years, 0.98 m/s
- Men between the ages of 30 to 50 years, 0.81 m/s
- Men over 50 years old, 0.67 m/s

- Women under 30 years old, 0.70 m/s
- Women between 30 to 50 years old, 0.60 m/s
- Women over 50 years old, 0.56 m/s

On an outdoor stair with a 152 mm riser and 305 mm tread, average speeds increased for all ages and genders. For men, the average speeds were 1.10 m/s, 0.96 m/s, and 0.71 m/s for the age groups from youngest to oldest. The three female age groups, in the same order, had average speeds of 0.79 m/s, 0.77 m/s, and 0.66 m/s.

Tanaboriboon and Guyano [38] studied descent on four different stairs in Bangkok, Thailand. The first stair had a 200 mm riser and 300 mm tread, was 1200 mm wide and speeds ranged from 0.39 m/s to 0.87 m/s, with a mean speed of 0.58 m/s. The second stair was 3000 mm wide and had a 150 mm riser and the 300 mm tread width. On the second stair, speeds ranged from 0.44 m/s to 0.82 m/s, with a mean speed of 0.60 m/s. The third stair had a 140 mm riser and 300 mm tread, and was 1200 mm wide. The minimum speed observed was 0.44 m/s and the maximum was 0.82 m/s, with a mean speed of 0.61 m/s. The final stair had a 130 mm riser, 300 mm tread, and was 1400 mm wide. The speeds ranged from 0.46 m/s to 0.89 m/s, with a mean speed of 0.62 m/s.

Lee and Lam [39] video recorded stair use in Hong Kong mass transit railway stations during the morning peak (8:00 to 10:00), afternoon off-peak (14:00 to 16:00), and evening peak (17:30 to 19:30) hours. The stair had an effective width of 1940 mm with a riser height of 160 mm and a tread depth of 310 mm. When the stairs were at the peak capacity, the average speed of descent ranged from 0.48 m/s to 0.65 m/s. Individual speeds during stair descent varied from 0.38 m/s to 0.92 m/s and 0.29 m/s to 0.93 m/s for the unidirectional and heavy counterflow cases, respectively.

Ye et al. [40] video recorded stair descent from 8:00 to 10:00 a.m. in one subway station in Shanghai, China from October to November 2006. The stair had 150 mm risers, 300 mm treads, and was 3050 mm wide. Speeds primarily fell between 0.5 m/s to 1.2 m/s for densities up to 1.7 persons/m^2.

The National Bureau of Standards (NBS) [41] mainly observed three stairs under normal conditions in buildings in the United States. The first stair was 1900 mm wide with a 191 mm riser and 286 mm tread. The average discharge rate (or flow) was 0.60 persons/m-s with a maximum of 0.71 persons/m-s. These values corresponded to densities of 1.33 persons/m^2 and 1.86 persons/m^2. The second stair was 1520 mm wide with a 184 mm riser and 305 mm tread depth. The average and maximum discharge rates were 1.04 persons/m-s and 1.53 persons/m-s, respectively. The densities were also increased as the average density was 2.20 persons/m^2 and the maximum density was 2.83 persons/m^2 (2.74 and 3.53 persons/m^2 for assumed effective width). The third stair was 914 mm wide and had 178 mm risers and 292 mm treads. The average discharge rate was 1.70 persons/m-s and the maximum specific flow was 1.86 persons/m-s. The average and maximum densities were 2.63 persons/m^2.

In the NBS study [41], in addition to the stairs where densities were provided, eight other stairs were presented with only flow rates. These stairs were from a variety of building types as well as experimental conditions. The widths varied from 1260 mm to 2220 mm with riser heights and tread depths varying from 165 mm to 203 mm and 267 to 305 mm, respectively. This resulted in average flows from 0.77 persons/m-s to 1.59 persons/m-s.

The London Transport Board [42] observed passengers in nine London subway stations. The stairs were 1000 mm to 2000 mm wide and had between 19 to 23 uninterrupted steps or two sets of 12 steps. The free flow speed was reported as 0.98 m/s. At conditions of maximum flow, the average speed was 0.67 m/s. At maximum flow conditions, the flow was 1.1 persons/m-s and the density was 1.6 persons/m^2. Also, the authors noted that, for stairs less than 1220 mm, occupants exited proportional to exit lanes 530 mm wide and, above this threshold, it was proportional to the entire width. The authors also found that the flow rate was approximately constant for most densities studied. As density increased, speed was found to proportionally decrease.

2.2.4 Laboratory Experiments

Frantzich [43] conducted a study that was divided into two parts. For the first part of the study, students were videotaped ascending and descending a 1300 mm stair with 270 mm tread depth and 170 mm riser height under controlled conditions. Individuals descended at 1.0 m/s. For groups, the movement speed varied from 0.82 to 0.91 m/s with densities ranging from 2.2 persons/m^2 to 2.5 persons/m^2. The second part of the study consisted of the general population after a performance in a theater. The stair was 2250 mm wide with a tread depth of 300 mm and a riser height of 150 mm. The movement speed varied from 0.3 m/s to 1.3 m/s.

In a second study by Frantzich [44], subjects were students age 20 to 30 years old, with no known movement disabilities. The first, base case, used a 1300 mm wide stair. The three alternates were: using a 900 mm wide stair; having two stationary individuals force the flow to move around them, thus increasing the density; and having slower individuals in the stair that were passed. The primary stair used in the investigation had a tread depth of 280 mm and a riser height of 175 mm. The narrower stair used in the investigation had a tread depth of 225 mm and a riser height of 205 mm. In the trials without any obstructions, the minimum interpersonal spacing was found to be 370 mm. For the case where the stair width was reduced, the interpersonal spacing[4] decreased to 250 mm. For descending the 1300 mm wide stair without obstructions, the movement speed varied from 0.27 m/s to 1.09 m/s with a mean speed of 0.69 m/s and a standard deviation of 0.15 m/s. For the 900 mm wide stair, the speed varied from 0 m/s to 2.27 m/s with a mean speed of 0.72 m/s and a standard deviation of 0.27 m/s.

Boyce, Shields, and Silcock [45] had volunteers in the United Kingdom with and without disabilities use different egress components. For stairs, forty-two subjects were able to participate. The eight subjects without disabilities had a mean descent speed of 0.70 m/s with a range of speeds from 0.45 m/s to 1.10 m/s. The thirty disabled subjects who were not assisted by another person had a mean speed of 0.33 m/s with a range from 0.11 m/s to 0.70 m/s. Within this group, nineteen subjects did not use a mobility aid and had a mean speed of 0.36 m/s; their speeds ranged from 0.13 m/s to 0.70 m/s. Nine subjects used a walking stick and had a mean speed of 0.32 m/s; their speeds were between 0.11 m/s and 0.49 m/s. One subject on crutches and

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[4] i.e., the distance between the center points of an evacuee and the closest evacuee directly behind in the stairwell during the evacuation

one subject that used a rollator had speeds of 0.22 m/s and 0.16 m/s, respectively. For the four personally-assisted subjects, the average speed was 0.13 m/s and the range of speeds was 0.11 m/s to 0.23 m/s.

Wright, Cook, and Webber [46] conducted a laboratory study in a purpose-built egress stair in a two-story office configuration. Eighteen subjects walked down a smoke-filled single flight of stairs under six different lighting conditions. The smoke varied in mean optical density from 1.1 m^{-1} to 1.2 m^{-1}. The different lighting conditions were normal lighting, emergency lighting, electroluminescent wayguidance system, miniature incandescent wayguidance system, and two light emitting diode wayguidance systems. Under normal and emergency lighting, the average speeds were approximately 0.3 m/s. The other four systems had average speeds that ranged from approximately 0.35 m/s to 0.42 m/s.

Fujiyama and Tyler [47] had subjects ascend and descend four sets of stairs. The first stair had 12 steps with a riser height of 185 mm and a tread depth of 230 mm. The second stair also had 12 steps with 175 mm and 250 mm riser height and tread depth, respectively. For the third stair, there were 15 steps with a riser height of 157 mm and a tread depth of 267 mm. Finally, the fourth stair had 9 steps and 152 mm riser height and 332 mm tread depth. There were 18 subjects between ages 60 to 81 years and 15 subjects between the ages of 25 to 60 years. For descending the first flight of stairs, occupants were asked to move at their normal pace. For the second set, the occupants were asked to move at their fast pace. For the normal pace trials, speeds for the younger group ranged from 0.76 to 0.96 m/s, while the older group had comparable speeds of 0.60 m/s to 0.88 m/s. With the exception of one descending stair, the differences between the two groups was not significant for the normal speeds. For the fast pace trials, the younger group had average speeds from 1.12 m/s to 1.30 m/s and the older group averaged 0.80 m/s to 1.11 m/s. For all stairs, the difference between the speeds of the two groups was significant at the 95% level or higher.

2.2.5 Behavioral Aspects

Once stair evacuation begins, occupant interactions within the stair can also impact movement speeds. Proulx [3], for example, found stairway movement involves a complex set of behaviors, such as resting, investigation, and communication. Movement on stairways is also affected by the amount of personal space needed per occupant, whether or not a person is carrying something (such as a child or personal items), the mobility of the person traveling either up or down a flight of stairs, and interactions with others in the stair.

One of the key interactions is merging behavior, the interactions between those in the stair and those attempting to enter the stair. While the exact manner in which merging behavior occurs may not be well understood [48], a number of studies have observed general trends in stair merging. For example, different types of merging are possible. Occupants in the stairs may defer to occupants entering the stairs [25, 28, 30]. Occupants on the floors may defer to those already in the stair [34]. Finally, neither may defer and the occupants on the floor and those already in the stair split evenly. Kagawa, Kose, and Morishita [36] report that there were instances where occupants in the stairs would not let occupants from the floors enter and that there were instances where occupants entering from the floor caused severe disruptions to the flow in the stairs. Boyce et al. [49] report that merging was split between those in the stairs and those on the floor, but the ratio depended on occupant speed and landing geometry. Additionally, merging behavior can impact stair movement. As occupants merged into the stair, the flow could slow down or become stagnant [16].While not studied for this paper, additional analysis of videos collected for this study could provide additional data on these deference behaviors.

2.2.6 Summary

Table 2 summarizes movement speeds reported in the literature, considerably updated from [50]. The methods used by the different authors varied significantly. Beyond just differences in the types of occupancies being studied, measurement methods varied. Thus, comparison of the data is naturally limited in scope. With the exception of several studies of the evacuation in the 110 floor World Trade Center Towers, the buildings included in the literature review ranges from single story buildings to 21 stories in height. Reported speeds ranged from 0.1 m/s to 1.4 m/s and occupant densities ranged from 0.5 persons/m^2 to 2.6 persons/m^2.

At least three key features of these studies influenced the current study. First, much of the literature data is several decades or more old. There has been considerable discussion on the applicability of the older data with the assumption that current populations could be slower than that represented by the older data. Newly-collected data can be compared with historical data partly to assess the applicability of historical data to current building populations. Second, the literature data include only buildings up to 21 stories in height. Taller buildings were of particular interest. The buildings selected for study included a wide range of building heights. Finally, none of the literature studies include data beyond average values or ranges of values. With more sophisticated egress models under development, this study endeavors to provide detailed data for model development and validation.

Table 2. Summary of stair movement speed literature

Source[a]	**Building Description**[b]	**Data Collection Method**	**Sample Size**	**Movement Speed**[c]	**Stairwell Description**[d]	**Notes**
Actual Events						
Averill, et al. 2005	L: USA T: Office Tower 1	Telephone interviews	368	M: 0.2	Two stairwells: W: 1100 One stairwell: W: 1400	- 803 interviewees - Interviewees were occupants from floors 10 – 91 - Movement speed includes rest and stopping periods
Shields, Boyce and McConnell 2009	L: USA T: Office	Interviews	6	R: 43 s/flr – 150 s/flr		- Participants had self-identified mobility impairments prior to the event - Movement speeds were gathered from data on 5 of the 6 participants
Galea, et al. 2009	L: USA T: Office Tower 1	Interviews	30	M: 0.29		

Table 2. Summary of stair movement speed literature, continued

Source[a]	Building Description[b]	Data Collection Method	Sample Size	Movement Speed[c]	Stairwell Description[d]	Notes
			Fire Drills			
Pauls 1971	L: Canada T: Commercial Building F: Occupants on floors 1 to 21	Observers	910	R: 0.61– 0.81	RH: 178 TD: 254 W: 1190	- 35 occupants used elevators for egress - 2 stairwells
Pauls and Jones 1980	Building 1 T: Office Building F: 14 floors	Not specified	1526	Above 7th Floor: Slowest: 0.23 m/s Below 7th Floor: M: 0.44 Last Floor: M: 0.66 D: 1.38	W: 1140	- Total of 5 dogleg stairwells - 1453 able-bodied occupants used four of the stairwells - 73 occupants, either disabled or assisting the disabled, used the fifth stairwell
	Building 2 T: Office Building F: 20 floors					- Total of 2 dogleg stairwells - Observers during steady-state conditions descended at approximately the same rate as those in Building 1
Proulx 1995	L: Canada T: 4 Residential Buildings F: 6 to 7 stories high	Video cameras	~340	Of the three buildings where speed could be measured, occupant speeds ranged from 0.52– 0.62 Children ages 2 – 5 years old: M: 0.45 Elderly: M: 0.43	Not specified	- Occupants tend to use whichever staircase they were accustomed to using regardless of proximity - Occupants tended to move in groups - There was no crowding in the stairwells during occupants' descent.

Table 2. Summary of stair movement speed literature, continued

Source[a]	Building Description[b]	Data Collection Method	Sample Size	Movement Speed[c]	Stairwell Description[d]	Notes
Proulx, et al. 1995	L: Canada Building 1 F: 14 floors	Video cameras	29	14 men and 15 women averaged: 1.07 m/s 19 group members averaged: 1.0 m/s 10 individuals averaged: 1.18 m/s	Not specified	No statistical difference in movement speeds between men and women
	L: Canada Building 2 F: 14 floors		28	M: 1.05	Not specified	No statistical difference in movement speeds between men and women
	L: Canada Building 3 F: 12 floors		76	M: 0.95 Men descending stairs: M: 1.05 m/s Women descending stairs: M: 0.86 m/s	Not specified	Descending stairs, men moved statistically faster than women, but no significance between men and women movement speeds was found when comparing results from all 3 buildings
Proulx, Kaufman, and Pineau 1996	Building 1 L: Canada T: Government F: 7 floors	Video Cameras	165	M: 0.78	Not specified	Women traveled significantly faster than men (0.81 m/s vs. 0.72 m/s)
	Building 2 L: Canada T: Government F: 7 floors		502	M: 0.93	Not specified	Men traveled significantly faster than women (0.96 m/s vs. 0.90 m/s)
Shields, et al. 1997	F: 5 floors	Not specified	276	Behind Wheelchair M: 0.33	Not specified	77 % of the building population used one of the two stairwells located in the building
				Before Wheelchair M: 1.1		

Table 2. Summary of stair movement speed literature, continued

Source[a]	**Building Description**[b]	**Data Collection Method**	**Sample Size**	**Movement Speed**[c]	**Stairwell Description**[d]	**Notes**
Proulx, et al. 1999	L: Canada F: 13 floors	Not specified	144	M: 0.57 R: 0.39 – 1.13 D: 2.05	Not specified	Stairwell 1 – Only Photoluminescent
		Not specified	65	M: 0.72 R: 0.64 – 1.30 D: 1.00		Stairwell 2 – Reduced Emergency Lighting and Photoluminescent
		Not specified	82	M: 0.70 R: 0.41 – 1.14 D: 1.23		Stairwell 3 – Only Reduced Emergency Lighting
		Not specified	101	M: 0.61 R: 0.45– 0.84 D: 1.30		Stairwell 4 – Normal Emergency Lighting
Khisty 1985	L: USA T: 21 dormitories F: 3 – 12 floors	Time lapse photography and observers		Normal Conditions Max speed: 0.64 m/s D: mode: 1.66 median: 1.38 Emergency Conditions Max speed: 0.70 m/s D: mode: 1.96 median: 1.40	RH Range: 165 – 190 TH Range: 279 - 305 W Range: 1220 – 2130	- 80% of occupants believed there was a real incident - Flow increased under emergency conditions (from 0.90 to 1.00 persons/m-s)

Table 2. Summary of stair movement speed literature, continued

Source[a]	Building Description[b]	Data Collection Method	Sample Size	Movement Speed[c]	Stairwell Description[d]	Notes
Proulx, et al. 2007	F: 11 floors	Not specified	1191	Stair: Mean Speed: 1 0.40 2 0.57 3 0.66 4 0.66 R: 0.17 – 1.87 D: range during busiest 5 minutes: 1.56 – 1.60 max: 2.30	W: 1100	- Six stairwells total - Four stairwells observed - Slow speed in stair1 due to mobility impairments
Hostikka, et al. 2007	T: office building F: 7 floors	Video cameras and RFID tags	281	For density < 0.5: ~Range: 0.5 – 1.5 For 0.5 < density < 2.5: ~Decrease in speed from 0.75 – 0.5 Median of fitted curve: 0.64 m/s - Flow rate range: 0.80 – 0.83 persons/m-s	Not specified	- Two of the four egress exits were blocked by cold smoke - Queues formed when slower occupants left a path allowing others to pass and when allowing other occupants to enter into the flow - No gender difference in speed

Table 2. Summary of stair movement speed literature, continued

Source[a]	Building Description[b]	Data Collection Method	Sample Size	Movement Speed[c]	Stairwell Description[d]	Notes
Normal Conditions						
Fruin 1987		Video cameras		Indoor Stairwell M: <u>Men:</u> < 30 yrs: 0.98 30 – 50 yrs: 0.81 > 50 yrs: 0.67 <u>Women:</u> < 30 yrs: 0.70 30 – 50 yrs: 0.60 > 50 yrs: 0.56	RH: 178 TD: 286	
				Outdoor Stairwell M: <u>Men:</u> < 30 yrs: 1.10 30 – 50 yrs: 0.96 > 50 yrs: 0.71 <u>Women:</u> < 30 yrs: 0.79 30 – 50 yrs: 0.77 > 50 yrs: 0.66	RH: 152 TD: 305	Average speeds increased on outdoor stairwell

Table 2. Summary of stair movement speed literature, continued

Source[a]	Building Description[b]	Data Collection Method	Sample Size	Movement Speed[c]	Stairwell Description[d]	Notes
Tanaboriboon and Guyano 1991	L: Bangkok, Thailand	Not specified		Stairwell 1 M: 0.58 R: 0.39 – 0.87	RH: 200 TD: 300 W: 1200	
				Stairwell 2 M: 0.60 R: 0.44 – 0.82	RH: 150 TD: 300 W: 3000	
				Stairwell 3 M: 0.61 R: 0.44 – 0.82	RH: 140 TD: 300 W: 1200	
				Stairwell 4 M: 0.62 R: 0.46 – 0.89	RH: 130 TD: 300 W: 1400	
Lee and Lam 2006	L: Hong Kong T: Mass transit railway stations	Not specified	8642	Mean range: 0.48 – 0.65 Unidirectional flow range: 0.38 – 0.92 Counter flow range: 0.29 – 0.93	RH: 160 TD: 310 W: 1940	
Ye et al.	L: Shanghai T: Subway station	Video		R: 0.5 – 1.2	RH: 150 TD: 300 W: 3050	

Table 2. Summary of stair movement speed literature, continued

Source^{a}	**Building Description**^{b}	**Data Collection Method**	**Sample Size**	**Movement Speed**^{c}	**Stairwell Description**^{d}	**Notes**
NBS 1935		Not specified		Stairwell 1 Average flow: 0.60 persons/m-s D: 1.33	RH: 191 TD: 286 W: 1900	
				Stairwell 2 Average flow: 1.04 persons/m-s D: 2.20	RH: 184 TD: 305 W: 1520	
				Stairwell 3 Average flow: 1.70 persons/m-s D: 2.63	RH: 178 TD: 292 W: 914	
London Transport Board 1952	L: London T: Subway stations	Not specified		Free flow speed: 0.98 Maximum flow: 1.1 persons/m-s Maximum flow speed: 0.67 Maximum flow density: 1.6	W Range: 1000 - 2000 19 – 23 consecutive steps or two sets of 12 steps	- Flow rate was ~constant for most densities - Speed was inversely proportional to density

Table 2. Summary of stair movement speed literature, continued

Source[a]	**Building Description**[b]	**Data Collection Method**	**Sample Size**	**Movement Speed**[c]	**Stairwell Description**[d]	**Notes**
			Laboratory Studies			
Frantzich 1994	F: 2 floors (only 1 floor was evacuated)	Video cameras		Group speed range: 0.82 – 0.91 Individuals traveled at 1.0 m/s Group density range: 2.2 – 2.5	RH: 170 TD: 270 W: 1300	Controlled Conditions
	T: Theatre	Not specified		R: 0.3 – 1.3	RH: 150 TD: 300 W: 2250	Uncontrolled Conditions, Sample consisted of general population after a theatre performance
Frantzich 1996	F: 2 floors (only 1 floor was evacuated)	Not specified	428	0.69 (SD: 0.15) R: 0.27 – 1.09	W: 1300	Sample consisted of students aged 20 – 30 years old with no known movement disabilities
				0.72 (SD: 0.27) R: 0 – 2.27	W: 900	
Boyce, Shields and Silcock 1999	L: UK	Not specified	8	0.70 R: 0.45 – 1.10	Not specified	Non-Disabled
			30	0.33 R: 0.11 – 0.70		Not-Assisted – Disabled, Total
			19	0.36 R: 0.13 – 0.70		Not-Assisted – Disabled, Without Mobility Aid
			9	0.32 R: 0.11 – 0.49		Not-Assisted – Disabled, Walking Stick
			1	0.22		Not-Assisted – Disabled, Crutches
			1	0.16		Not-Assisted – Disabled, Rollator
			4	0.13 R: 0.11 – 0.23		Assisted – Disabled,

Table 2. Summary of stair movement speed literature, continued

Source[a]	**Building Description**[b]	**Data Collection Method**	**Sample Size**	**Movement Speed**[c]	**Stairwell Description**[d]	**Notes**
Wright, Cook and Webber 2001			18	0.3		Smoke Conditions, Normal and Emergency Lighting
				Mean range: 0.35 – 0.42		Smoke Conditions, Other Lighting Conditions
Fujiyama and Tyler 2004		Not specified	15	Ages 25 – 60 Normal pace R: 0.76 – 0.96	Stairwell 1: RH: 185 TD: 230 12 steps Stairwell 2: RH: 175 TD: 250 12 steps Stairwell 3: RH: 157 TD: 267 15 steps Stairwell 4: RH: 152 TD: 332 9 steps	- Differences in normal pace speeds between the two age groups was not significant - Differences in fast pace speeds between the two age groups was significant
				Ages 25 – 60 Fast pace Mean range: 1.12 – 1.30		
			18	Ages 60 – 81 Normal pace R: 0.60 - 0.88		
				Ages 60 – 81 Fast pace Mean range: 0.80 – 1.11		

a – Author and year

b – L = location, T = building type, F = number of floors

c – M = mean in m/s, R = range in m/s unless otherwise indicated, D = average density in persons / m^2 unless otherwise indicated

d – RH = rise height in mm, TD = tread depth in mm, W = stair width in mm

2.3 Building Code Provisions on Stair Egress

As stated earlier, one purpose of this report is to provide data that can form a technical foundation for updated building code provisions related to stair egress. This section provides a discussion of current code requirements for egress stair design in order to understand the important engineering variables that are part of that design.

Constitutionally, regulation of building construction and maintenance is a state and local responsibility in the United States. However, there is significant efficiency achieved by having consistency in construction requirements between states or cities. On the other hand, local hazards, climate, and construction materials and methods may vary regionally. Thus, a system of national model codes has evolved, where each state or local jurisdiction uses the model code as a starting point for regulation and may alter certain provisions to suit local conditions. In the United States, there are two primary model building codes: the International Building Code ® (IBC) [51] and the Life Safety Code ® (LSC) [52]. The code requirements for stair construction in both model codes differ modestly and, therefore, both are described below. It is important to note that any state or local modifications to the national model codes are not described below. Design of stairways for emergency occupant egress encompasses two primary aspects: capacity and usability. Capacity requirements ensure that the stairways are sized to allow the prescribed number of occupants (often referred to as the design load) to use the stairs in a timely manner. Usability requirements, on the other hand, ensure that the stairway construction does not impede safe use of the stairway.

2.3.1 Determination of Stairway Capacity in the National Model Building Codes

Both national model codes, the International Building Code and the Life Safety Code determine egress capacity similarly[5]. The required width of the stairs is determined by, and proportional to, the capacity of the spaces served by the stairways. Using the 2012 values in the International Building Code, the width of the required minimum number of stairways may be determined by the following four steps:

1. Calculate the number of persons on a floor. The number of persons is a function of the nature of the space usage (for example, business use [one person for every 100 gross square feet] versus mercantile use [one person for every 60 gross square feet]) and the total floor area[6]. Thus, a building with 36000 square feet of space on an upper floor would be required to provide stair capacity for 360 persons for an office occupancy or 600 persons for a mercantile occupancy.

2. Determine the minimum number of required stairs. The minimum number of required stairways is determined by the number of occupants and occupant travel distance. Since a

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[5] The discussion of stairway requirements is intended to illustrate common stairway design considerations and should not be interpreted as design guidance for any real building design. Requirements for building egress systems can vary significantly depending upon specific characteristics of the building; consequently design of stairways should only be conducted by licensed professionals and reviewed and approved by an authorized building official.

[6] In some circumstances, the number of persons using a stair may cumulatively include additional floors when the only path of egress travel requires that occupants move through another floor or area served by a particular stair access point.

single stairway is not permitted for any structure taller than two stories, two stairways are commonly required. A third stairway is required when the occupant load exceeds 500 persons and a fourth stairway is required when the occupant load exceeds 1000 persons[7]. Additional stairways may also be required if an occupant travel distance from their egress starting point and the exit access point exceed specific threshold values.

3. Using the appropriate capacity factor, determine the total required stair width. The number of occupants (Step 1, above) is multiplied by a capacity factor (0.3 inches per occupant for use groups without sprinkler and emergency communication voice/alarm systems and 0.2 inches per occupant for many [not all] use groups with sprinkler and emergency communication voice/alarm systems). For example, stairway capacity for 600 persons would require a minimum of 180 total inches of stairway width or 120 total inches of width for buildings with the requisite sprinkler and alarm systems.

4. Divide the total required stair width amongst at least the minimum number of required stairways. For a floor area with an occupant load of 600 persons (where the total building height was 420 feet tall or less), the three required stairways may each be 60 inches wide if the building did not have an appropriate sprinkler system and alarm system. Stairways may also have differing widths, as long as (a) the loss of one stairway does not eliminate more than 50 % of the egress capacity, and (b) each stair is at least 44 inches in width. Alternatively, if the building was protected by a sprinkler and alarm system meeting certain provisions, the three required stairways would have to provide 120 inches of total width. Since the minimum width of a stair serving more than 50 persons is 44 inches, three 44 inch stairs would likely be provided.

The preceding example demonstrates the critical importance of ensuring a sound scientific stairway width. Both the IBC and the LSC directly correlate incremental increases in stair width with increased capacity. In particular, two thresholds are currently designated for minimum stair width in buildings: 44 inch wide stairways as a minimum width in both the IBC and the LSC (though only for stairways serving greater than 50 people and less than 2000 people in the LSC) and 56 inch wide stairways (for buildings serving equal to or greater than 2000 people in the LSC). Therefore, evaluation of the performance of the critical threshold widths, as well as various other widths, is important for assessing the efficacy of common building code requirements for stairway construction.

2.3.2 Usability Requirements in the National Model Building Codes

Usability requirements ensure that the stairway construction does not impede safe stairway usage. The provisions range from lighting requirements to obstructions, including, but not limited to:

- Minimum ceiling height;
- Minimum clear width in the stairs;
- Limits on protrusions from the walls in hallways and landings;

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[7] In the IBC, when the building height exceeds 420 feet, either an additional stairway (one more than would otherwise be required for a building lower than 421 feet) or occupant evacuation elevators should be provided.

- Handrail requirements, including the size, shape, and continuity of the handrail;
- Signage indicating the floor number and stairway identifier;
- Minimum lighting levels, including emergency power or luminescence;
- Size, direction of swing, and maximum force requirements for stair access and exit doors;
- Dimensional uniformity of stair edges;
- Height and depth limits of stair risers/treads[8]
- Durability and integrity of stairway wall construction; and
- Size and spacing of landings.

While usability requirements serve to increase the likelihood that the stairway will perform without negative impact on occupant movement, usability requirements are not the primary focus of this paper.

2.4 Egress modeling

As discussed in Chapter 1 of this report, performance-based analysis of building egress is based upon the use of analytical tools and simulation models to assess the level of fire safety provided by a building design [53, 54]. Performance-based design (PBD) is often based on a comparison between the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET) in order to verify the achievement of the desired performance. ASET, calculated via the use of fire modeling techniques, is the time after which the untenable conditions of the given building develop. RSET, calculated via the use of egress modeling techniques, is the time needed by occupants to perform a safe evacuation (i.e., the evacuation time for a building or a section of a building). Here, egress modeling techniques include both analytical tools or equations and simulation models.

2.4.1 Analytical tools

Even though a building evacuation consists of both the pre-evacuation and movement periods, the analytical tools or equations, to be presented here and often referred to as the Hydraulic model [55], focus primarily on the movement period. There is little consideration of the behavioral aspects of the movement period, and almost no consideration of the pre-evacuation period.

The first-order or simplified hydraulic model, that will be discussed here, represents a simplified approach to calculating evacuation time from a structure. It focuses on the component within the building that places the most severe constraint on the flow of people around the building, and uses the movement of people through this constraint to determine movement time [55]. Using this method, the analyst (i.e., engineer) must calculate the time that occupants take to reach the

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[8] The IBC and the LSC (i.e., NFPA 101 ®) state that stair riser heights shall be 178 mm (7 inches) maximum and 100 mm (4 inches) minimum, and rectangular tread depths shall be 280 mm (11 inches) minimum. The IBC also provides specifics on the ways in which to measure these values: the riser heights are measured vertically between the nosings of adjacent treads, and the tread depths are measured horizontally between the vertical planes of the foremost projection of adjacent treads and at a right angle to the tread’s nosings.

controlling component, the time that occupants take to traverse this component, and then the time for the last person to reach safety from the controlling component. The components of the hydraulic model are as follows: effective width[9], population density, speed, flow characteristics, time for passage through a component, and transitions between components. To calculate the time that occupants take to reach the controlling component, analysts can use various equations available to calculate speed [56].

In multi-story buildings, the controlling component may be the entry to the stairs (for example, once occupants enter the stairs, it could be assumed they have reached a safe location) or the door at the base or bottom of the building's narrowest stair (for example, the calculation is intended to determine when occupants leave the building to a safe area outside the building footprint). Therefore, the analyst may be required to calculate the time that it would take building occupants to travel to the stairs, travel on the stairs for some distance, and exit through the door at the stair exit.

Based on the work of Fruin [37], Pauls [57], and Predtechenskii and Milinskii [58], the SFPE Handbook [59, 60] proposes calculating stair movement speeds for densities between 0.54 persons/m^2 to 3.8 persons/m^2 as a linear function of density. For situations in which the density is less than 0.54 persons/m^2, the speed at 0.54 persons/m^2 is assumed.

$$s = k - akD \text{ for } D > 0.54 \tag{1}$$

where s is the speed of the occupant (m/s) along the line of travel, D is the population density in person per unit area, and k and a are constants. For stair travel, these constants change based upon rise and tread stair geometry. For example, k is 1.00 m/s for a 190 mm riser and 254 mm tread depth, 1.08 m/s for a 178 mm riser and 279 mm tread depth, 1.16 m/s for a 165 mm riser and 305 mm tread depth, or 1.23 m/s for a 165 mm riser and 330 mm tread depth. The value of a is taken to be 0.266 m^2/person.

To calculate the time that occupants take to traverse the controlling component, an equation for flow is used. According to the SFPE handbook [59], the time for passage for a group of persons to pass a point in an exit route is expressed as the following:

$$\frac{P_{total}}{F_{ave}} = T_{exit} \tag{2}$$

where P_{total} is the total number of people using the exit route, F_{ave} (people/s) is the mean flow of people out the exit route, in this case, a door, and T_{exit} (s) is the total travel time for people to exit that particular stair.

The SFPE Handbook [60] also includes a correlation in terms of a power law fit to the total population and effective stair width:

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[9] Effective width is defined here as the usable width of a component of a building (e.g., a door). Often, a certain distance is subtracted from each side of the component to accommodate body sway during evacuation movement or small intrusions into the pathway such as handrails.

$$a\left(\frac{P_{total}}{w_{eff}}\right)^{b} = \frac{F_{ave}}{w_{eff}} \qquad (3)$$

where w_{eff} is the effective width of the stairs, and a and b are constants. In the SFPE Handbook, values for these constants are a = 0.206 and b = 0.27 [60]. This equation shows that mean evacuation flow (per meter of effective stair width) varies in a nonlinear fashion with evacuation population (per meter of effective stair width). This relationship allows the analyst to calculate the mean flow of people out of the exit route (in this case, the door) based upon knowledge of the effective width of the stair and the total population (per effective width) using that stair, to calculate the total movement time for a particular stair in the building.

Finally, to calculate the time for the last person to reach safety from the controlling component, the analyst often can use the speed equations presented above, as eq. (1). For most buildings, this is either a calculation of speed on a flat surface, or in some cases where the door leads directly to the outside.

2.4.2 Simulation models

To achieve a potentially more realistic evacuation calculation, in comparison with the hydraulic model, engineers have looked to evacuation computer models to help assess key aspects of a building's life safety attributes. Currently, there are a number of egress models to choose from, each with unique characteristics and specialties. These models can range from an efficient use of the hand calculations (thus having the same limitations as the hand calculations) to models that have complex equations and occupants with simulated decision-making capabilities.

The list below, based on Ref. [53], describes the ways in which the current egress models (i.e., simulation techniques) vary amongst one another. Table 3 summarizes the following characteristics for current egress models.

1) Model availability – there are a variety of ways in which egress models can be released to the public. While a few of them are free, most are made available for some fee (either a one-time fee or a yearly rate), and others are proprietary and used only on a consultancy basis.

2) Modeling method – The modeling sophistication used to calculate evacuation times for buildings varies from model to model. On one end of the spectrum, models may simulate only the movement period of an evacuation, similar to the models described in 2.4.1; on the other end, models may simulate both the movement and behavioral aspects of an evacuation.

3) Model purpose – The current egress models vary in the types of buildings for which they are used, i.e., from high-rise buildings to ships to planes, etc.

4) Type of grid/structure of the model – Egress models also vary in how they represent the geometry of the building or structure.

This is an important distinction to make because Lord et al. [2] has shown that differences in building configuration using different grid/structure methods can significantly influence results of egress models. Three main categories of grid/structures are the following: coarse network models, fine network models, and continuous models [61]. Recent studies also investigated the use of a combination of different approaches, i.e., hybrid models [62]. These categories represent a different level of resolution in the representation of the behaviors of the agents.

In coarse network models, the building's floor space is simulated as a network of nodes and arcs, representing different parts of the infrastructure. Stairs may be represented as individual elements of the network or through a combination of sub-elements.

The fine network approach represents the space as a grid of uniform cells. The movement of the agents is simulated through a series of steps in the cells of the network. This permits an improved tracking of the location of the occupants during the stair evacuation process. Agents are represented as individual entities with the possibility to simulate local and global behavioral factors.

Continuous models represent the agents using a system of coordinates. These models offer the flexibility to simulate occupant behaviors that may be sensitive to the location of the occupants on the stairs, orientation and inter-distance among the agents.

5) Model view of the occupants – Next, the models vary in the ways that they view the occupants in the building. If the occupants are viewed globally, then the model views the occupants as a homogenous group of people. A model that incorporates the opposite view (or individualistic view) can track individuals throughout the simulation and assign them various characteristics that can affect their evacuation timing.

6) Occupants' view of the building – Additionally, models differ in the ways that occupants in the simulation view the building during evacuation. If occupants have a global view of the building, then they are assumed to be familiar with all exit paths available; whereas, if occupants have an individual view of the building, then they decide the best exit routes based upon other factors (e.g., routes that are more familiar to the occupant than others).

7) Behavior of the occupants – Egress models simulate occupant behavior in different ways. On one end of the spectrum, they may be incapable of simulating behavior altogether (i.e., and focus only on the movement period of an evacuation), and on the other end of the spectrum, they may be capable of simulating human intelligence and learning over time. Models in the latter group are rare and not typically used in the analysis of fire evacuation.

8) Movement of the occupants – The ways in which occupants move throughout the simulated building also vary among egress models, based upon the underlying movement algorithms embedded into the model.

For most methods, the main input required by the analyst is generally the unimpeded walking speed of the occupants on stairs and the assumptions adopted for the representation of the geometric layout of the stairs [i.e., type of grid/structure of the model]. Models may either employ the hydraulic equations provided by Gwynne and Rosenbaum [59] or adopt a speed reduction factor of the unimpeded walking speeds on horizontal egress components [55]. An alternative solution adopted by model developers is the use of the same assumptions/algorithms adopted for the representation of people movement on horizontal egress components for the case of stair evacuations.

9) Incorporation of fire effects – Some egress models do incorporate the effects of fire into the evacuation simulation, and in different ways, and some do not.

10) The use of computer-aided design (CAD) drawings – Similarly, some egress models allow the user to import files from a computer-aided design (CAD) program, or other files containing the building layout, into the model, and others do not.

11) Visualization methods – Egress models also differ on how they visualize the evacuation scenario, if at all. Evacuation output from the structure can vary from textual, to graphical (either in two dimensions or three).

12) Validation methods – Finally, egress models vary in the ways that they have been validated; i.e., the underlying data in the model are accurate representations of the real world situations.

A previously published NIST report provides a comprehensive model review of 26 egress models and the ways that these models differ on all 12 features previously described [53]. All 26 models highlighted in reference [53] are categorized by each feature in Table 3.

Table 3. Main features of egress models

Model	*Available to public*	*Modeling Method*	*Purpose*	*Grid/ Structure*	*Perspective of M/O*	*Behavior*[a]	*Movement*[a]	*Fire data*	*CAD*	*Visual*	*Valid*
EVACNET4	Y	M-O	1	C	G	N	UC	N	N	N	FD
WAYOUT	Y	M	5	C	G	N	D	N	N	2-D	FD
STEPS[c]	Y	B	1	F	I	C, P	P, E	Y1,2	Y	2,3-D	C,FD,PE
PEDROUTE	Y	PB	3	C	G	I	D	N	Y	2,3-D	N
Simulex[b]	Y	PB	1	Co.	I	I	ID	N	Y	2-D	FD,PE, 3P
GridFlow	Y	PB	1	Co.	I	I	D	N	Y	2,3-D	FD, PE
FDS+Evac[c]	Y	PB	1	Co.	I	I, C, P	ID	Y3	N/Y	2,3-D	FD,PE,OM
Pathfinder 2009[c]	Y	PB	1	Co.	I/G	I	D,ID	N	Y	2,3-D	C,FD,PE,OM
SimWalk[c]	Y	PB	1,3	Co.	I	C, P	P	N	Y	2,3-D	FD,PE,3P
PEDFLOW[c]	Y	B	1	Co.	I	C, P	ID	Y2	Y	2,3-D	PE
PedGo[c]	Y,N1	PB/B	1	F	I/I,G	I/C, P	P,E (CA), C	Y2	Y	2,3-D	FD,PE,OM,3P
ASERI[c]	Y	B-RA	1	Co.	I	C, P	ID	Y1,2	Y	2,3-D	FD, PE
BldEXO[b]	Y	B	1	F	I	C, P	P, E	Y1,2	Y	2,3-D	FD,PE,OM,3P
Legion[c]	Y,N1	B	1	Co.	I	AI, P	ID, C	Y1	Y	2,3-D	C,FD,PE,3P
SpaceSensor[c]	Y	B	3	Co.	I	C, P	C, Ac_K	N	Y	2,3-D	FD,OM
EPT[c]	Y,N1	B	1	F	I	AI	UC,C	Y2	Y	2,3-D	FD
Myriad II[c]	Y, N1	B	1	C, F, Co.	I	AI	D, UC, IP, Ac_K	Y1	Y	2,3-D	PE, 3P
MassMotion[c]	Y, N1	B	1	Co.	I/I,G	AI,P	C	N	Y	2,3-D	C,FD,PE,OM
PathFinder	N1	M	1	F	I/G	N	D	N	Y	2-D	N
ALLSAFE	N1	PB	5	C	G	I	Un_F	Y1,2	N	2-D	OM
CRISP	N1	B-RA	1	F	I	C, P	E,D	Y3	Y	2,3-D	FD
EGRESS 2002	N1	B	1	F	I	C, P	P,D (CA)	Y2	N	2-D	FD
SGEM[c]	N1	PB	1	Co.	I	I	D	N	Y	2-D	FD,OM
EXIT89[c]	N2	PB	1	C	I	I/C, P	D	Y1	N	N	FD,3P
MASSEgress[b]	N2	B	1	Co.	I	C, AI	C	N	Y	2,3-D	PE,OM
EvacuatioNZ[c]	N2	B	1	C	I/I,G	I, C, P	D, UC	Y2	Y	2-D	FD, PE,OM

[a] Only the underlying methods used by the algorithm are listed. In some instances users can define other options

[b] Model developers/NIST provided an update on the model's development in Spring 2009.

[c] Model developers/NIST provided an update on the model's development in Fall 2010.

Key to Table 3.

Availability to the Public: (**Y**): The model is available to the public for free or a fee, (**N1**): The company uses the model for clients on a consultancy basis, (**N2**): The model has not yet been released

Modeling Method: (**M**): Movement model, (**M-O**): Movement/optimization models, (**PB**): Partial Behavioral model, (**B**): Behavioral model, (**B-RA**): Behavioral model with risk assessment capabilities

***Purpose**:* (**1**) Models that can simulate any type of building, (**2**) Models that specialize in residences, (**3**) Models that specialize in public transport stations, (**4**) Models that are capable of simulating low-rise buildings (under 15 stories), (**5**) Models that only simulate 1-route/exit of the building.

Grid/Structure: (**C**): Coarse network, (**F**): Fine network, (**Co**): Continuous

Perspective of the model/occupant: (**G**): Global perspective (aware of all other elements in the model), (**I**): Individual perspective (aware of only the local surroundings). Each model is categorized by both the perspective of the model and of the occupant. If only one entry is listed in this column, both the model and occupant have the same perspective.

Human behavior: (**N**): Not considered, (**I**): Implicit, (**C**): Conditional or rule-based, (**AI**): Artificial intelligence, (**P**): Probabilistic

Movement: (**D**): Density, (**UC**): User's choice, (**ID**): Inter-person distance, (**P**): Potential, (**E**): Emptiness of next grid cell, (**C**): Conditional, (**Ac_K**): Acquired knowledge, (**Un_F**): Unimpeded flow, (**CA**): Cellular automata

Fire Data: (**N**): The model cannot incorporate fire data, (**Y1**): The model can import fire data from another model, (**Y2**): The model allows the user to input specific fire data at certain times throughout the evacuation, (**Y3**): The model has its own simultaneous fire model

CAD: (**N**): The model does not allow for importation of CAD drawings, (**Y**): The model does allow for importation of CAD drawings

Visual: (**N**): The model does not have visualization capabilities, (**2-D**): 2-dimension visualization available, (**3-D**): 3-dimension visualization available

Validation: (**C**): Validation against code requirements, (**FD**): Validation against fire drills or other people movement experiments/trials. (**PE**): Validation against literature on past experiments (flow rates, etc.), (**OM**): Validation against other models, (**3P**): Third party validation, (**N**): No validation work could be found regarding the model

Although Table 3 shows that most models have performed some form of experimental validation, more work is needed. Most model validation is performed by the model developers using data that was used to develop the model, older data (i.e., the data used to develop the hydraulic model presented earlier), and/or proprietary data not made available to the public. This certainly limits validation efforts, and potentially leaves the user wondering if sufficient validation exercises have been performed, especially for the specific project for which the model is being used. Only in a few cases is third party validation performed. Additionally, validation against other models or codes, while it may seem beneficial, is only as good as the codes and models against which the results of the models are being compared. Methods that can be used to assess the validity of egress models is an active research area and standardization of the process is just beginning (see, for example, [63, 64]).

Table 3 also shows that the egress models use a variety of different methods with which to move people throughout the building during the simulation. These movement methods are often based in older data, if any data at all, and use a variety of different algorithms, rather than one standard, accepted method. This, and the fact that egress models use various methods to represent the building configuration (i.e., grid/structure), can lead to differing results in evacuation time, leaving the analyst confused as to which egress model is more accurate in its evacuation results.

Not shown in Table 3 is the onerous burden placed on the analyst to use many of these simulation models. All of the egress models shown in Table 3 require a significant amount of user input, depending upon the scenario simulated, that requires the user to search for various types of evacuation data, which are scarce in number and scope. Even worse, there are sets of "special capabilities" simulated in each model, i.e., the simulation of counterflow or elevator usage, also not shown in Table 1, for which there are little or no data available. In these cases, the analyst should confirm that these capabilities are supported by applicable and sound data.

Finally, a recent review on the use of egress models for building evacuation studies [65] shows that there are specific evacuation behavior that need further experimental studies (and data) in order to enhance model capabilities. The first factor is the need for data that investigate the effect of fatigue on the stair evacuation process. Given the increasing height of buildings and the gradual reduction in the physical ability of the population [66], this appears as a key variable that has been largely ignored in egress models. Second, the analysis of occupant interactions during stair evacuations is another factor that needs further experimental studies. For instance, the understanding of occupant behaviors on stair landings is crucial since it may substantially affect egress model predictions of the evacuation process (and subsequent evacuation time calculations) given the occurrence of behaviors such as merging, deference/overtaking, etc. [48, 49]. Third, egress models permit only a general assessment and review of egress strategies that involve people with disabilities. In fact, the capabilities of egress models are generally not designed to fully represent occupant group dynamics on stairs which involve heterogeneous populations, e.g. populations with different characteristics, impairments, occupants using different stair evacuation devices (e.g. rescue chairs), etc. To address this issue, further experimental data about the impact of the presence of people with disabilities on stair evacuations are needed.

3 Experimental Data Collection and Methods

Data on people movement on stairs were collected from 14 office and residential building evacuations in the United States. The buildings involved in this study ranged from 6 stories to 62 stories in height. This section includes information on how the video was collected, description of how the underlying movement data was extracted from the video, and details of additional data obtained on the stair geometry in the buildings.

3.1 Video Observation Procedures

In this study, data from fire drill evacuations were collected by positioning video cameras out of the way of building occupants to record an overhead view of occupant movement in an exit stair during an evacuation. In most cases, video cameras were placed on specific floors throughout the building to capture a view of that floor's main landing, the door into the stair at that level, and 2-6 steps on each side of the main landing (leading to and from the main landing). This camera placement captured the times in which the occupant was seen moving past a particular floor landing as well as the time when he/she was seen moving into the stairs.

Figure 2 shows an example of the camera view from one of the buildings in the sample. In this particular building's camera view, the times that the occupants entered the camera view were recorded 2-3 steps away from the main landing (leading to the landing), at the landing doorway, and 2-3 steps away from the main landing (leading away from the landing), as shown by highlighted lines on the steps and at the landing doorway.

Figure 2. Typical stair landing showing camera view with entry locations for occupant movement timing from stairs above, stair entry door, and exit from camera view for one of the buildings in the study.

Figure 3 shows the locations of all cameras throughout each stair in each building in the study. The reference point for each stair is the location of the building's main lobby. This reference point is provided in Figure 3 to graphically display instances where evacuees were required to travel past (or below) the building's main lobby floor and therefore, exit the building at a level lower than the main lobby level.

From Figure 3, one can see that video cameras were placed at least every other floor, sometimes every floor, in each stair, with the exception of Building 6. Since Building 6 was a 62-story building, the number of cameras available for observation made it impossible to place cameras on every other floor in all four stairs. Therefore, cameras were placed nominally every 6 floors throughout each stair, in addition to locations where the stair configurations changed and additional camera observations were necessary; e.g., positioning cameras on floors 22, 23, and 24 in Stairs 6 and 6a. Details of camera placement are available in Appendix A.

Before recording began, all video cameras were set to record in "pixelation" mode. Additionally, cameras were placed in overhead positions so that the recording of faces was avoided. This process made the observation of personally identifiable features (i.e., faces) virtually impossible. With that said, NIST observers were still able to track evacuees from one camera location to another via other distinguishing evacuee characteristics, e.g., clothing type and color.

During the evacuation, all videos were digitally recorded onto tapes or directly onto the camera's hard drive. After each evacuation was over, the digital videos were transferred from each of the cameras and placed onto a secure server only accessible to the NIST team. On this server, each video is labeled by the building number, stair designation, and camera location within that stair. No information that would identify the building was attached to any video recorded by NIST.

3.2 Occupant Data from Video Records

After video data were taken from each building evacuation drill and placed onto NIST's secure server, NIST transcribed specific data from the videos into a spreadsheet format for each stair monitored during the drill. For each stair recorded, data were collected 1) for each occupant evacuating in that stair and 2) for each time during the evacuation drill that the occupant was seen at a specific floor in the stair (a camera position), typically both entering and exiting the camera view. A total of 22277 individual measurements for 5249 evacuees in the 30 stairwells are included in the data set.

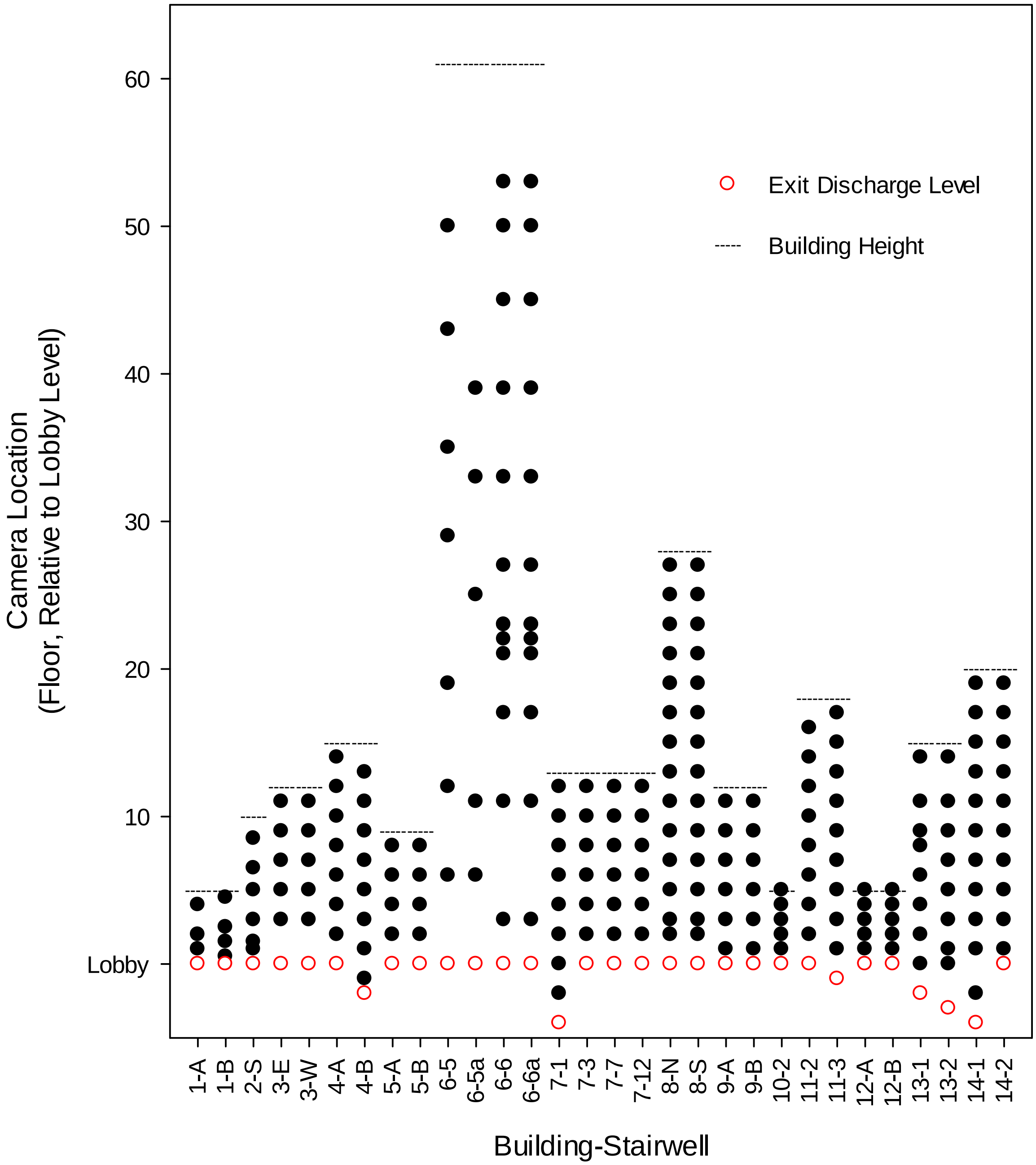

Figure 3. Camera locations in stairs included in the study. Stair numbering includes the building number (assigned chronologically by NIST) and the stair number (A, B, N, S, 1, 2, etc.) as described in the building.

The data collected each time an occupant was seen on a specific camera were the following information:

- The time that he/she was seen entering the camera view and the location at which this time was taken. For occupants coming from the floor above, this was often a line “drawn” at a specific step leading to the main landing (e.g., four steps away from the main landing heading into the camera view). For occupants coming from that floor, into the stair, the line “drawn” was placed at the edge of the door to the landing or at the edge of the landing leading to the next flight of stairs (i.e., leading down from that floor). Figure 2 shows an example visible camera area on a stair landing.
- The time that he/she was seen leaving the camera view – the exit point. This was often a line “drawn” at a specific step leading from the main landing (e.g., two steps away from the main landing heading away from the camera view).
- His/her location on the stair. This includes whether he/she was traveling on the inside, outside or the middle of the stair. This variable could change for a given occupant at subsequent floors. No information was collected on location outside of camera views.
- His/her handrail usage. This includes whether he/she was using the inside or outside handrail, or both of them at the same time. NIST personnel determined that the individual was using the handrail if, at any point while visible on the camera at that floor, the occupant placed his or her hand on the handrail. As was the case with the exit lane variable, this variable could change for a given occupant at subsequent floors and the information on handrail use was only available when visible in a camera.

Additionally, there were data collected for each occupant (overall) during the evacuation drill. These included the following information:

- Gender. Occupants were classified as being female, male, or unknown.
- Floor of origin / travel distance. This was recorded as the number of floors since the occupant was first seen on the camera.
- Whether he/she was carrying anything (Yes or No). Whether an individual was carrying anything was determined by NIST personnel from the videos. It was assumed that a person identified as carrying an object did so throughout the evacuation. There was no distinction made for the size of object or how it was being carried. Objects included small objects held in one hand, bags on either a shoulder or held in one hand, and backpacks that left both hands free.
- His/her body size. The data input into this column included a) less than 1/2 the stair width or b) more than 1/2 the stair width.
- Whether he/she was in a group at any time during the drill (Yes or No).
- Whether he/she was helping someone at any time during the drill (Yes or No).
- Whether he/she was travelling in the opposite direction of the evacuating occupants, here termed counterflow. For example, in some buildings, first responders were sent up the stairs sharing the stairs with evacuating occupants.

3.3 Stair Geometry Data

Arguably, the primary data collected for this study was the timing of occupant movement traversing the stairs during evacuation. Along with the movement timing, stair geometry including distance travelled on the stairs and landings, stair widths, stair tread depth, stair riser height, and landing size were measured in all of the buildings to allow calculation of movement speed, density, and flow. Figure 4 illustrates the calculation of travel distance within a stair.

Templer [67] observed individuals and their travel paths in isolation descending stairs. While there were marked differences depending on the direction that the stair turned, none of the individuals were observed to follow straight-line paths during stair travel. Instead, the paths were rounded (arcs) as individuals walked towards the middle of the landing and then towards the descending stair. From this, the following equation was used to calculate travel distances on landings in the building [68]:

$$L_i = \pi \frac{w_i}{2} \tag{4}$$

Where L_i is the travel distance on landing i and w_i is the stair width at this location.

Equation (4) was used to compute the landing distances traveled during stair evacuation. Additionally, the diagonal distance traveled along the stairs was also calculated using the stair tread riser and depth dimensions.

Estimated uncertainty of travel speed measurements comes largely from uncertainty in the travel path. For this report, we have assumed travel is in the center of the stairs and around the landings per eq. (4). Other possible travel paths along the inside or outside of the stair in this sample would allow the travel distance for an average building floor to range from approximately 9 m to 10.5 m. Uncertainty in occupant movement timing collected from video footage is estimated to be ± 0.1 s. From this, measurement uncertainty in the calculated speeds is estimated to be ± 0.02 m/s included as part of the uncertainties shown in Chapter 4, below. For this sample, the measurement uncertainty contributes less than 0.5 % to the total variation in measured movement speeds for the evacuee population studied.

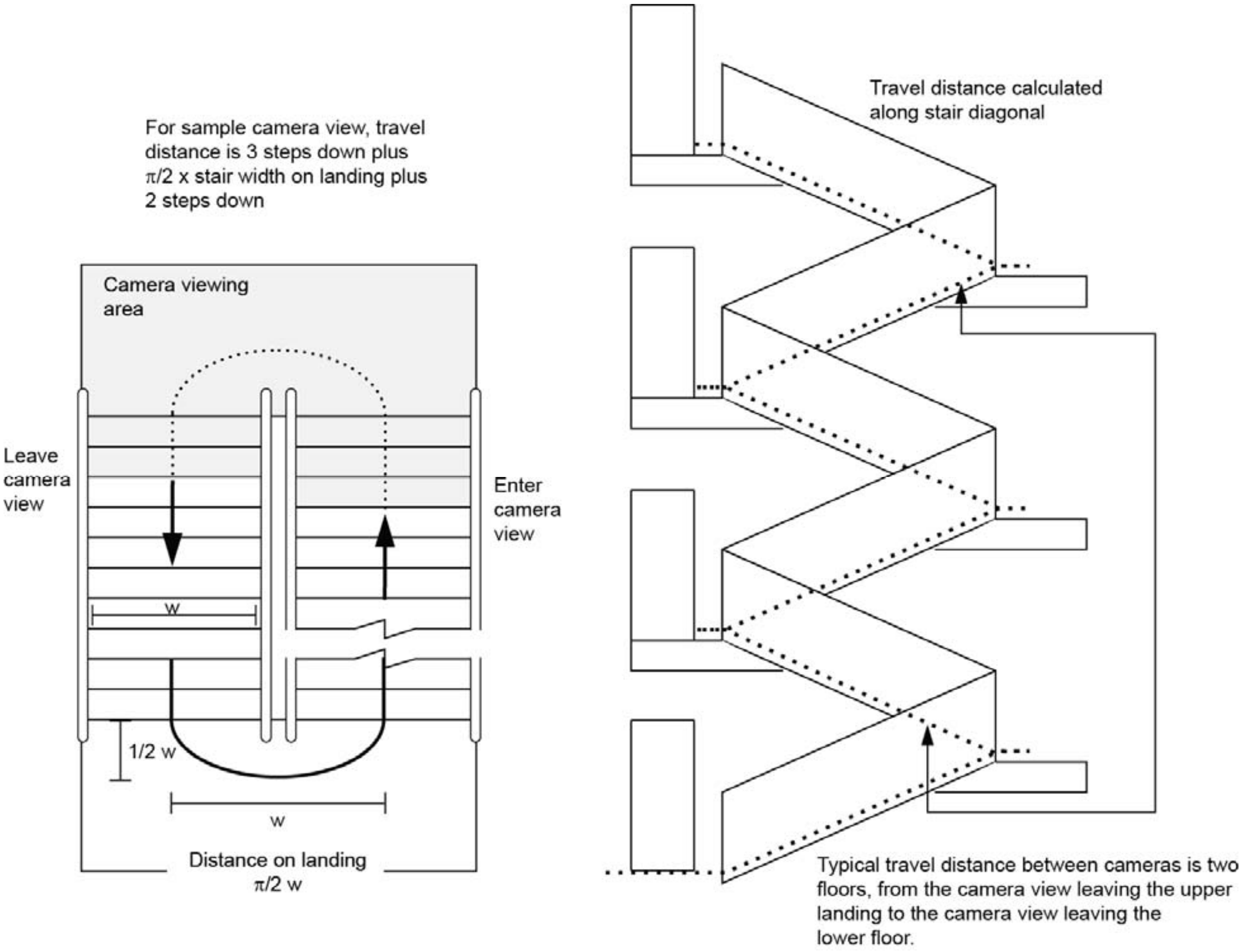

Figure 4. Overview of camera view and landing / stair travel distance during stair evacuation observations.

3.4 Buildings Included in the Study

Table 4 shows a summary of the buildings included in the study. The following sections provide details of each of the buildings. Details of travel distances, number of steps between floors, and additional horizontal paths in the egress path are included in Appendix A.

Table 4. Buildings included in the current study

Building	Location (year)	Building Type	Stories Above Exit Discharge	Stair / evacuees[q]	Stair Width (mm)	Flights / Steps per Floor (typical)	Tread Depth / Tread Rise (mm)	Counter-flow	Stair Travel Device
1	East Coast (2005)	Office	6	A / 126	1440 / 1130	2 /16	280 / 200		
				B / 108	1540 / 1230	2 /16[a]	280 / 200	Yes	Yes
2	Midwest (2007)	Education	11	S / 117	1270 / 965[b]	2 / 20[b]	240 / 190		
3	East Coast (2005)	Office	13	E / 116	1120 / 810	2 /18	310 / 170		
				W / 84	1120 / 810	2 /18	310 / 170		
4	West Coast (2008)	Office	24[c]	A / 246	1120 / 810	2 / 20	280 / 180	Yes	
				B / 321	1120 / 810	2 / 20	280 / 180		
5	West Coast (2008)	Office	10	A / 384	1270 / 965	2 /22[d]	280 / 180		
				B / 350	1270 / 965	2 / 22[d]	280 / 180	Yes	
6	West Coast (2008)	Office	62	5 / 112	1040 / 880[e]	2 / 22	250 / 200		
				5A / 149	1030 / 880[f]	2 / 22	250 / 200		
				6 / 117	1040 / 880	2 / 22	250 / 200		
				6A / 217	1040 / 880	2 / 22	250 / 200		
7	East Coast (2008)	Office	18[i]	1 / 264	1120 / 810	2 / 16[i]	250 / 190		
				3 / 291	1120 / 810	2 / 16	250 / 190		
				7 / 262	1120 / 810	2 / 16	250 / 190		Yes
				12 / 181	1120 / 810	2 / 16	250 / 190	Yes	
8	East Coast (2008)	Office	30[j,k]	N / 676	1380 / 1070	2 / 18	270 / 180		
				S / 483	1380 / 1070	2 / 18	270 / 180		
9	East Coast (2009)	Residential	13	1 / 69	1370 / 1070	2 / 18	320 / 150	Yes	Yes
				2 / 56	1370 / 1070	2 / 18[l]	320 / 150	Yes	Yes
10	East Coast (2010)	Residential (assisted)	6	2 / 45	1120 / 950	2 / 18[l]	305 / 165	Yes	Yes
11	West Coast (2010)	Courthouse	22[m]	2 / 77	1270 / 1170	4 / 36[m]	280 / 180		
				3 / 83	1180 / 1070	4 / 36[m]	280 / 180		Yes

Table 4, continued

Building	Location (year)	Building Type	Stories Above Exit Discharge	Stair / evacuees	Stair Width (mm)	Flights / Steps per Floor	Tread Depth / Tread Rise (mm)	Counter-flow	Stair Travel Device
12	East Coast (2011)	Office	6	A / 61	1120 / 1040	2 / 20[n]	290 / 180		
				B / 12	1120 / 1040	2 / 20[n]	290 / 180		
13	East Coast (2011)	Residential	15[j,o]	1 / 35	1120 / 980	2 / 16[o]	300 / 170		Yes
				2 / 39	1120 / 980	2 / 16[o]	300 / 170		
14	Midwest (2011)	Courthouse	21[p]	1 / 157	1060 / 920	6 / 32[p]	300 / 170		Yes
				2 / 100	1040 / 900	6 / 32[p]	300 / 170		

a – Stair B had a total of 16 steps between floor 2 and floor 1 with 10 steps down from floor 2 to a mid-landing and an 6 additional steps from the mid-landing down to floor 1.

b – Stair width increased to 1680 mm / 1370 mm from floor 3 landing down to floor 1. Steps per floor increased to 22 from floor 3 landing down to floor 1.

c – Stair A terminated at the main building lobby on floor 2. Stair B exited directly to the outdoors at the rear of the building on floor 1.

d – In both stairs, there were a total of 27 steps between floor 2 and floor 1 with a mid-landing 13 steps down from floor 2 and an additional 13 steps from the mid-landing down to floor 1.

e – Stair 5 had 2 flights with a total of 34 steps between floors 44 and 43, 3 flights per floor with a total of 34 steps per floor between floors 43 to 41 and between floors 24 to 21, 5 flights with a total of 33 steps between floors 4 and 3, 6 flights with a total of 36 steps between floors 3 and 2, and 5 flights with a total of 37 steps between floor 2 and 1. Stair 5 had transfer hallways on floor 42, at a landing between 42 and 41, floor 22, at a landing between floor 22 and 21, and floor 4.

f – Stair 5A had 3 flights per floor with a total of 46 steps per floor between floors 44 to 42 and between floors 24 to 22, 4 flights with a total of 22 steps between floors 5 and 4, 5 flights with a total of 39 steps between floors 4 and 3, 6 flights with a total of 36 steps between floors 3 and 2, and 5 flights with a total of 31 steps between floors 2 and 1. Stair 5A had transfer hallways on floors 42, 22, and 4.

g – Stair 6 had 2 flights with a total of 14 steps between floors 45 and 44, 4 flights with a total of 22 steps between floors 44 and 43, 5 flights with a total of 33 steps between floors 43 and 42, 2 flights with a total of 13 steps between floors 25 and 24, 4 flights with a total of 22 steps between floors 24 and 23, 3 flights with a total of 24 steps between floors 32 and 22, 4 flights with a total of 22 steps between floors 22 and 21, 2 flights with a total of 31 steps between floors 6 and 5, 5 flights with a total of 22 steps between floors 5 and 4, 3 flights with a total of 24 steps between floors 4 and 3, 4 flights with a total of 24 steps between floors 3 and 2, and 4 flights with a total of 23 steps between floors 2 and 1. Stair 6 had transfer hallways on floors 44, 24, 22, and 4.

h – Stair 6A had 4 flights with a total of 22 steps between floors 44 and 43, 5 flights with a total of 33 steps between floors 43 and 42, 2 flights with a total of 13 steps between floors 25 and 24, 4 flights with a total of 22 steps between floors 24 and 23, 3 flights with a total of 24 steps between floors 23 and 22, 4 flights with a total of 22 steps between floors 22 and 21, 2 flights with a total of 31 steps between floors 6 and 5, 5 flights with total of 22 steps between floors 5 and 4, 2 flights with a total of 24 steps between floor 4 and 3, 4 flights with a total of 24 steps between floors 3 and 2, and 3 flights with a total of 23 steps between floors 2 and 1. Stair 6A had transfer hallways on floors 44, 24, 23, 20, and 4.

i – Stairs 3, 7, and 12 exited at the main floor lobby at floor 5. Stair 1 exited directly to the outdoors at the rear of the building on floor 1. Stair 1 had two flights with a total of 18 steps between floors 4 and 3 and between floors 2 and 1. Stairs 3, 7, and 12 had 2 flights with a total of 19 steps between floors 6 and 5.

j – Building did not have a 13th floor. Building height adjusted to total floors above the main exit discharge.

k – The North stair had 2 flights with a total of 16 steps between floors 4 and 3 and 3 flights with a total of 27 steps between floors 3 and 2. The South stair had 3 flights with a total of 32 steps between floors 4 and 3 and 3 flights with a total of 27 steps between floors 3 and 2. There were transfer hallways in both stairs between floors 4 and 3.

l – Both stairs had 3 flights with a total of 27 steps between floors 2 and 1.

m – Stair 2 terminated at floor 2. Stair 3 terminated at floor 1. Both stairs had 2 flights per floor with a total of 24 steps per floor between floors 7 and 2. Stair 3 had 3 flights with a total of 25 steps between floors 2 and1.

n – Stair A had 3 flights with a total of 35 steps between floors 2 and 1. Stair B had 3 flights with a total of 32 steps between floors 2 and 1.

o – Stair 1 terminated at floor T1, one level below the main building lobby. Stair 2 terminated at the opposite end of the building at floor T2, two levels below the main building lobby. Both stairs had 2 flights with a total of 21 steps between floors 1 and T1. Stair 2 has 2 flights with a total of 16 steps between floors T1 and T2.

p – Stair 1 terminated at floor T3, three levels below the main building lobby. Stair 2 terminated at floor 1 directly to the outside of the building. Both stairs had 3 flights with a total of 22 steps from floors 21 to 20 and 6 flights with a total of 40 steps between floors 20 and 7. Stair 1 had 3 flights with a total of 23 steps between floors 7 and 6, 3 flights with a total of 22 steps between floor 6 and 5, 3 flights per floor with a total of 23 steps per floor between floors 5 and 3, 3 flights with a total of 22 steps between floor 3 and 2, 6 flights with a total of 32 steps between floors 2 and 1, 3 flights with a total of 32 steps between floors 1 and T1, 4 flights with a total of 32 steps between floors T1 and T2, and 5 flights with a total of 31 steps between floors T2 and T3. Stair 2 had 3 flights per floor with a total of 23 steps per floor between floors 7 and 2 and 2 flights with a total of 32 steps between floors 2 and 1.

q – Overall count includes only that evacuees who travelled down at least one floor and exited the building at the exit floor for the stairwell. First responder counterflow, partial evacuation, or those with building responsibility who monitored the evacuation are not included in the count.

3.4.1 Building 1

Building 1 is a six-story office building with seven wings located on the East Coast of the United States. Each wing is shaped like a large rectangle. The lengths of the wings are all adjoining and parallel to each other, forming an even larger rectangle. The occupants of the building participate in full-building evacuations twice a year. On a typical day, the building houses as many as 9000 people.

The building has 14 stairs that exit into building lobbies that then exit to the outside on the ground floor. During the drill, NIST collected data from two of these stairs. The stairs were in separate, neighboring wings. The wings observed were mirror images of each other, with the same number of elevators, stairs, and exterior exit doors. The stairs in each wing were equally accessible from all rooms and floors. Both stairs deposited occupants into a lobby through a set of double doors.

A total of 9 camera locations were included in the two stairs observed. In Stair A, cameras were located at the main landings on floors 1, 2, 3, and 5. In Stair B, cameras were located at the main landing on floor 1, and on intermediate landings at floors 1.5, 2.5, 3.5, and 5.5.

The unannounced[10] full-building evacuation drill observed by NIST took place during the summer of 2005 during normal business hours (before lunch). There was no precipitation during the drill. There were 272 participants in the evacuation in the two stairs (129 in Stair A and 143 in Stair B; however, a total of 126 in Stair A and 108 in Stair B fully evacuated the building)[11]. During the drill, two groups of three firefighters each travelled up Stair B to floor 5.

3.4.2 Building 2

Building 2 is an 11-story educational building located in the Midwest of the United States. The building was equipped with classrooms and a library, as well as office spaces. A corridor encircled the building with offices on the outside of the corridors and classrooms or laboratories on the inside. The building elevators are located on one end of the building with an adjacent corner stair. A second stair was located diagonally opposite the first stair. Classrooms and an assembly space were located on the first three floors of the building.

NIST observed both stairs. However, all but six of the occupants used the stair nearest to the building elevators. This stair was designated as the South stair and is the only one analyzed for this report.

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[10] Unannounced drill: The occupants were made aware of the evacuation drill only by the sound of the fire alarm. Announced drill: The occupants were made aware of the drill ahead of time but typically were not informed of the specific time of the drill.

[11] The overall count of participants includes those building occupants who took part in the evacuation travelling down the stairs to the building exit (here termed “fully evacuated”) plus those with building responsibilities who monitored the evacuation but did not travel down the stairs to the exit plus any evacuees who did not travel the full distance to the exit at the base of the stairs.

On the day of the drill, NIST collected data from seven camera locations. Cameras were located at the main landings on floors 1, 2, 4, and 6, and at the mid-landings on floors 2.5, 7.5, and 9.5.

The evacuation drill observed by NIST took place during the fall of 2007 during normal business hours (before lunch). There was no precipitation during the drill. There were 128 participants in the unannounced full building evacuation in the South stair (a total of 117 in the South Stair fully evacuated the building).

3.4.3 Building 3

Building 3 is a 13-story office building located on the East Coast of the United States with 11 occupied floors above ground. The occupants of this building perform yearly full-building evacuation drills. On a typical day, the building population is approximately 375 people.

During the drill, evacuation from two stairs was observed (the East stair and the West stair). The stairs were equally accessible from all floors in the building. In both stairs, occupants exited from the stairs on the ground floor level (floor 1).

The unannounced evacuation drill observed by NIST took place during the fall of 2005 during normal business hours (before lunch). There was no precipitation during the drill. There were 226 participants in the unannounced full building evacuation in the two stairs (125 in the East Stair and 101 in the West Stair; however, a total of 116 in the East Stair and 84 in the West Stair fully evacuated the building).

3.4.4 Building 4

Building 4 is a 24-story office building. The occupants in this building perform yearly staged evacuation drills; however, they participate in a full-building evacuation drill every five years. On a typical day, the building houses a population of approximately 1500 people.

The building has two stairs; Stairs A and B. Stair A exits onto the 2nd floor lobby where occupants must travel through the lobby to exit the building. Stair B exits directly to the outside on the ground floor (Floor 1).

On the day of the drill, NIST collected data from 23 different camera locations in the two stairs observed. In Stair A, 11 cameras were placed on every other floor beginning at the exit floor (Floor 2) and ending with Floor 22. Stair B, 12 cameras were placed every other floor beginning at the exit floor and then continuing on every other even floor from Floor 2 to Floor 22. NIST observed people movement in both Stairs A and B.

The unannounced evacuation drill took place in the spring months of 2008 during normal business hours (before lunch). There was no precipitation during the drill. There were 621 participants in the two monitored stairs in the full building evacuation drill (257 in Stair A and 364 in Stair B; however, a total of 246 in Stair A and 321 in Stair B fully evacuated the building). During the drill, three firefighters travelled up Stair A to the 13th floor approximately 1.5 minutes into the evacuation drill. Also before the drill, firefighters were staged in the stairs on selected floor landings and began floor searches to ensure that all occupants evacuated as soon as the alarm sounded.

3.4.5 Building 5

Building 5 is a 10-story office building. The occupants in this building practice yearly full-building evacuation drills. On a typical day, the building houses a population of approximately 1000 people.

The building has two stairs; Stairs A and B, both of which exit directly out of the building on the first (or ground) floor.

NIST collected data from 10 camera locations in the two stairs observed. In both stairs, cameras were located on main landings beginning with the exit floor (floor 1) and then continuing every other odd numbered floor from floor 3 to floor 9. NIST observed people movement in both Stairs A and B.

The unannounced full building evacuation drill took place in the spring months of 2008 during normal business house (before lunch). There was no precipitation during the drill. There were 807 participants in the drill (436 in Stair A and 371 in Stair B; however, a total of 384 in Stair A and 350 in Stair B fully evacuated the building). During the drill, six firefighters travelled up Stair B to the 7th floor approximately 8 to 11 minutes into the evacuation drill; i.e., when the drill was almost completed. Also during the drill, firefighters assigned to specific floors began floor searches to ensure that all occupants evacuated as soon as the alarm sounded.

3.4.6 Building 6

Building 6 is a 62-story office building on the West Coast of the United States. On a typical day, the building houses a population of approximately 2800 people, 2/3 of which are below the 30th floor. The subdivision of office space varies from floor to floor.

The building has four main stairs available for egress (numbered 5, 5-A, 6, and 6-A). Two of the stairs share a common shaft. There are transfer hallways in the buildings that route the egress stairs around mechanical spaces. Occupant movement was observed in all four stairs; Stair 5 (which served floors up to floor 52), Stair 5A, and the two stairs that shared a common shaft, Stair 6 and Stair 6A (which served floors up to floor 52). For floors 52 and above, there are only two stairs (stairs 5A and 6). At the time of the drill, there were no occupants above floor 54.

Data were collected from a total of 42 camera locations in the four stairs. Cameras were placed several floors apart in the four different stairs. Camera locations are shown below.

- Stair 5: Floors 1, 7 13, 20, 30, 36, 44, 51

- Stair 5A: Floors 1, 7, 12, 26, 34, 40
- Stair 6: Floors: 1, 4, 12, 18, 22, 23, 24, 24.5, 28, 34, 40, 46, 51, 54
- Stair 6A: Floors 1, 4, 12, 18, 22, 23, 24, 24.5, 28, 34, 40, 46, 51, 54

The announced drill took place on a 2008 spring morning during regular working hours before lunch. There was no precipitation during the drill. There were a total of 607 participants observed over the approximately 20 minutes duration of the voluntary drill. A total of 595 people fully evacuated the building, with 112 in Stair 5, 149 in Stair 5A, 117 in Stair 6, and 217 in Stair 6A.

3.4.7 Building 7

Building 7 is an 18-story office building housed in three wings adjoining a fourth corridor at one end of the wings. The building houses approximately 4000 people and has twelve stairs available for egress, numbered one through twelve. In Building 7, there have been small fires and other incidents in the past that initiated the building alarm. Additionally, the building practices fire drills on a yearly basis. Within the year before the observed drill, the local fire department noted one intentional alarm that initiated a building evacuation and one small fire that also initiated a building evacuation without injury to the occupants.

Occupants were observed in four of the 12 stairs; specifically Stairs 1, 3, 7, and 12. These stairs were observed due to their placement in the building – in order to observe stairs from each of the wings in the building. This building is situated on a hill so that the lobby of the building is on the 5th floor and the actual exit for Stair 1 is five floors below on the opposite (downhill) side of the building at ground level (floor 1). Stair 1 exited directly out of the building.

On the day of the drill, NIST collected data from 30 different camera locations in the four stairs observed. In Stairs 3, 7, and 12, 7 cameras were placed every other floor beginning at the exit floor (Floor 5) and ending with Floor 17. In Stair 1, 9 cameras were placed every other floor beginning at the exit floor (Floor 1) and ending with Floor 17.

The evacuation drill observed by NIST took place in the spring months of 2008 during normal business hours (before lunch). There was no precipitation during the drill. Within the four stairs observed, there were 1168 participants in the unannounced full building evacuation drill (286 in Stair 1, 312 in Stair 3, 373 in Stair 7, and 197 in Stair 12; however a total of 239+25[12] in Stair 1, 291 in Stair 3, 262 in Stair 7, and 181 in Stair 12 fully evacuated the building).

During the drill, a total of 17 firefighters travelled up Stair 12 from the 5th floor to the 12th floor; one group of seven firefighters were followed by another group of ten. Also, the local area Community Emergency Response Team (CERT) members stood at the entrance to Stair 2 and relayed to building occupants that Stair 2 was blocked and they needed to find another stair (likely causing a higher number of occupants to use the stairs near Stair 2 - Stairs 1 and 3 - than

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[12] 25 occupants using Stair 1 exited at the building lobby (on the 5th floor) rather than continuing down to the actual exit for the stair at the ground floor (floor 1).

normally expected during an evacuation). Last, a person from the CERT team evacuated via Stair 7 assisted by three members of the fire department using a stair travel device.

3.4.8 Building 8

Building 8 is a 30-story office building on the East Coast of the United States (although the floors above ground are numbered up to 31; i.e., without a floor numbered as the 13th floor). On a typical day, the building houses a population of approximately 2100 people.

The building has two stairs (North and South, designated N and S here) that both exit on the 2nd floor onto the street level.

On the day of the drill, NIST collected data from 30 different camera locations in the two stairs observed. In both stairs, cameras were placed on floors 30 to 14 (every other floor), 11, 9, 7, 5, 4, and 2. Cameras were placed on odd floors between floors 11 to 5 because the building did not have a 13th floor. Cameras were also placed on even floors at the base of the stair (Floors 2 and 4) since Floor 2 was the exit level.

The evacuation drill observed by NIST took place in the fall months of 2008 during normal business hours (before lunch). There was no precipitation during the drill. The full-scale, simultaneous building evacuation was unannounced. Additionally, the elevators were not available for the population to use during the drill. Only people with disabilities were able to use the elevators for evacuation, and only the freight elevator was available for their use. Overall, there were 1218 participants in this evacuation drill (685 in the North Stair and 533 in the South stair; however, a total of 676 in the North Stair and 483 in the South stair fully evacuated the building).

3.4.9 Building 9

Building 9 is a 13-story residential building on the East Coast of the United States that contains 175 living units. The building is designated for older adults with a typical population of approximately 200 residents.

The building has two stairs, Stairs 1 and 2, both of which exit directly out of the building on ground floor.

On the day of the drill, NIST collected data from 14 different camera locations in the two stairs. Cameras were placed on the ground (exit) floor and on floors 1 (one floor above ground level), 3, 5, 7, 9, and 11 in both stairs.

The announced, mandatory evacuation drill took place in the fall of 2009 in the morning (before noon). There was no precipitation during the drill. Building management made a decision to announce this evacuation drill so that building occupants would not be upset by the drill and instead, be ready and prepared to take part. The evacuation scenario used for the drill was a gas leak near the building, which rendered the elevators inoperable for egress.

The drill lasted for 75 min; however, video cameras were only able to capture 56 minutes of the evacuation. In the building, 71 people participated in Stair 1 and 56 people in Stair 2; however, a total of 69 in Stair 1 and 56 in Stair 2 fully evacuated the building). These numbers include all evacuees of the building and building staff that were either evacuating themselves or assisting residents; however, these numbers do not include firefighters assisting evacuees.

Throughout the drill, firefighters from various local fire stations arrived on scene and assisted building occupants down the stairs. Firefighters did interact briefly with evacuating occupants inside the stairs; however, when this would occur, the evacuating occupants were given priority (i.e., firefighters would step aside and allow evacuating occupants to pass by). Building occupants evacuated via the stairs on their own, with some assistance from firefighters or other occupants, or via stair travel devices guided by firefighters[13]. A total of 45 firefighters from 8 different companies and additional support personnel were deployed for this evacuation drill and used this drill as a training opportunity on how to evacuate occupants with mobility impairments using one type of stair travel device. Staff members assisted some occupants; however, firefighters assisted evacuees in stair travel devices.

3.4.10 Building 10

Building 10 is a six-story residential building on the East Coast of the United States containing 133 living units. The building is designated as an assisted living facility for older adults.

Occupants evacuated in one of the three stairs that exit to the ground floor. Due to technical difficulties, only two of the three could be monitored (Stair 2 and Stair 3). However, the majority of the residents evacuated via stair 2 during the drill.

On the day of the drill, NIST collected data from 12 different cameras locations, with cameras placed on every floor of Stair 2 and Stair 3.

The building evacuation drill began around 10 am in the Fall of 2010. There was no precipitation during the drill. Firefighters and staff members knocked on the doors of residents who volunteered to participate in the evacuation. Building management decided to announce this drill and not sound the alarm so that older occupants who did not volunteer would remain calm. The exercise scenario was flooding in the basement from a water main break. In the scenario, water filled the elevator pits and approached the main mechanical room, thus rendering the elevators inoperable. If the flood persisted, the water would reach the electric panels and require all power to be shut down. Therefore, management chose to evacuate residents from the building via stairs. The video cameras captured 50 minutes of the evacuation, which was cut short due to time

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[13] Stair travel devices were used to assist individuals with mobility impairments down the stairs. The chairs were escorted by two to three firefighters at any one time. The type of stair travel device used was one in which the individual sits upright on landings, and is tilted slightly back on stairs so that the chair may slide on the diagonal of the steps with ease. The specifics about chair manufacturer are not discussed in this paper.

constraints of the training exercise (i.e., not all residents evacuated the building). Throughout the drill, firefighters from different companies as well as support personnel arrived on scene to help building occupants travel down the stairs. Residents evacuated via the stairs on their own, with a cane, with assistance from firefighters or other occupants, or by stair travel devices. The firefighters used this drill as a training opportunity for evacuating mobility-impaired individuals on stair travel devices.

In the six-story building, 47 residents were evacuated, with 45 in Stair 2 and 2 in Stair 3. The reason for the difference in stair usage was because the firefighters designated Stair 2 as their main evacuation stair, using it almost exclusively for evacuation, while the other two stairs were used to carry vacant stair travel devices back up to waiting residents. In Stair 2, two occupants on stair travel devices were transferred from Stair 2 to Stair 3 because of slight congestion. These numbers do not include firefighters assisting evacuees. Only those residents in Stair 2 are included in the analysis in this report.

3.4.11 Building 11

Building 11 is a 22-story office (courthouse) building on the West Coast of the United States. On a typical day, the building houses a population of approximately 600 people.

This building has 22 stories, 19 of which are occupied, and has four stairways for evacuation. Two exit stairs, Stairs 1 and 2 are public stairs that provide access from floor 18 (Stair 2) or 19 (Stair 3) to the exit (either the lobby or the basement floor exit). The other two exit stairs, Stairs 3 and 4, are secured stairs. Stair 3 provides access to all occupied floors. Stair 4 services floors 7 to 1. During the evacuation, NIST set up video cameras in two of the four exit stairs, specifically Stairs 2 and 3, to capture people movement on exit stairways and through stair/exit doors.

Data were collected from 19 different camera locations in the two stairs observed. In Stair 2, cameras were placed on every even floor starting with floor 18 down to floor 2 (for a total of 9 cameras), and in Stair 3, cameras were placed on every odd floor beginning at floor 19 and ending at floor 1 (for a total of 10 cameras).

The evacuation drill took place in the fall months of 2010 during normal business hours (before lunch). There was no precipitation during the drill. There were 224 participants in the unannounced full building evacuation drill (135 in Stair 2 and 89 in Stair 3; however, a total of 77 in Stair 2 and 83 in Stair 3 fully evacuated the building). During the drill, an individual from the 11th floor was evacuated via a stair travel device in Stair 3.

3.4.12 Building 12

Building 12 is a 6-story office building located on the East Coast of the United States.

The building has two stairs, Stair A and Stair B. Both stairs serve all six floors of the building and exit at the first floor.

On the day of the drill, cameras were placed at every floor of both stairs to capture a view of each floor's main landings. The camera also recorded the time in which people moved through the space (i.e. when people enter and exit landings). NIST observed people movement in both stairs.

The unannounced full-building evacuation drill took place in the spring of 2011 during normal business hours (before lunch). There was no precipitation during the drill. 76 occupants were observed in the two monitored stairs during the evacuation (64 in Stair A and 12 in Stair B; however, a total of 61 in Stair A and 12 in Stair B fully evacuated the building).

3.4.13 Building 13

Building 13 is a 15-story residential high-rise building on the East Coast of the United States (although the floors above ground are numbered up to 16; i.e., without a floor numbered as the 13th floor). The building contains 203 living units as well as a commercial space on the T1 level of the building.

The building has two stairs, Stairs 1 and 2. Stair 1 ends at the T1 level (one level underground in reference to the building's front entrance) and Stair 2 ends at the T2 level (two levels underground in reference to the building's front entrance). The building was built on a hill that allowed for three separate exits levels.

On the day of the drill, NIST collected data from 18 different camera locations in the two stairs. In Stair 2, cameras were located at level T1 (one floor underground; the exit level), every other floor from floor 1 up to floor 9, and floors 10, 12, and 15 (actually the 14th floor above ground so cameras were placed every other floor). In Stair 2, cameras were located on floor T2 (two level underground, the exit level), floor 1, and every other floor from floor 2 to 15.

The announced, voluntary evacuation drill took place in the spring of 2011 in the morning (before noon). There was no precipitation during the drill. Building management made a decision to announce this evacuation drill so that building occupants would not be upset by the drill and instead, be ready and prepared to take part. The evacuation scenario used for the drill was a fire scenario in the building which would require a full building evacuation. When the fire alarm sounded, most building occupants evacuated via the stairs on their own. The fire department was also present for the evacuation drill, and evacuated one occupant using a stair travel device.

In the 15-story building, 36 people evacuated in Stair 1 and 39 people in Stair 2 without assistance; however, a total of 35 in Stair 1 and 39 in Stair 2 fully evacuated the building. Additionally firefighters assisted one additional occupant in a stair travel device in Stair 1; these numbers do not include firefighters assisting evacuees.

3.4.14 Building 14

Building 14 is a 21-story office (courthouse) building in the Midwest of the United States. On a typical day, the building houses a population of approximately 600 people.

This building has 21 stories above ground and three main stairways for evacuation. Two exit stairs, Stairs 1 and 2 are public stairs that provide access from floor 21 to the exit (either the lobby or the lower level 3 floor exits since Stair 2 exits on the rear of the building, three floors below the grade in the front of the building). The third exit stair, Stair 3, is secured. Stair 3 provides access to all floors. Additional stairs in the building include a number of convenience stairs that connect adjacent floors but do not travel the full height of the building and stairs used for egress of below grade levels (Stairs 4 and 5). NIST collected data from Stairs 1 and 2. Both stairs have a unique triangular configuration for the above-ground floors. Additional details of the stairwells are available in Appendix A.

On the day of the drill, NIST collected data from 23 different camera locations in the two stairs. In Stair 1, 12 cameras were placed on every other floor from L3 up to 20. In Stair 2, cameras were placed on floor 1 (the exit floor) and every other floor from floor 2 up to 20.

The unannounced evacuation drill took place in the fall of 2011 during normal business hours (before lunch). There was no precipitation during the drill. There were 305 participants in the two monitored stairs (175 in Stair 1 and 130 in Stair 2; however, a total of 157 in Stair 1 and 100 in Stair 2 fully evacuated the building).

4 Overall Results

NIST observed 14 full building evacuations of both office and residential occupancies to provide quantification of evacuee movement and better understanding of behavior during egress. From the 14 buildings, a total of 30 stairwells were observed in the study. The data collected and analyzed from these stairwells, available on the NIST website at http://www.nist.gov/el/ fire_research /egress.cfm, is a primary output of this research and is intended as a resource for engineers and model developers. This section provides a discussion of the calculations of movement timing, speed, and density and presents the overall results of these calculations. Detailed analyses of the results is included in section 5.

4.1 Calculations

This section details calculations performed on the data collected from the video tapes. These calculations facilitated a consistent analysis of the data to better understand occupant movement during the stair evacuations. The analysis included translation of the recorded data to a set of observation times for each evacuee as they entered, traversed, and exited a stair relative to the timing of an initial alarm for the drill, calculations to quantify overall and local movement speeds and flows, determination of occupant density in the stairs, and statistical analyses of the data to understand the relative impact of various occupant and stair characteristics on these calculated values. Appendices B through D include additional details about the calculations and associated uncertainty analyses.

4.1.1 Occupant Movement Timing

The timing of each evacuee at each camera location (both entering and leaving the camera view) was transcribed directly from video records. To allow for comparison and calculation, these times were converted to times relative to the building fire alarm signaling the beginning of the evacuation. The converted times were used in all subsequent analyses.

4.1.2 Pre-Observation Delay

Pre-observation delay was defined for each occupant as the time from the initial alarm until the occupant was seen entering the stair to evacuate the building. Occupants who entered the stair between camera locations were not included in calculated mean values since they had to descend at least one floor in the stair prior to entering a camera view. In general, pre-observation delay is expected to be a longer time than the typical pre-evacuation delay time, since it includes time for movement to the stair in addition to the time for the performance of any activities.

4.1.3 Travel Time

Travel times are defined as the elapsed time between observations points. For consistency, the start time for all occupants was taken to be the time they *left* the view of the highest camera location for that occupant (i.e., a camera *exit* point). Thus for occupants who entered the stair between camera locations, there is some period of time not captured before they enter the first camera location. "Overall travel time" in a stair is the difference between this start time and the time the occupant left the stair at the lowest camera location (a stop time). For the calculation of local speeds, the time interval between successive camera locations was used to calculate a local travel time. Again, start and stop times were typically taken as the time the occupant was seen leaving successive camera locations.

4.1.4 Movement Speed

Overall movement speed for each occupant was determined from the total travel distance (from where he/she entered the stairwell to the exit at the bottom of the stairwell) divided by the difference between entry and exit times. Overall speeds for occupants who left the stairwell prior to the exit or who waited an excessive amount of time on the entry floor (typically floor wardens or others with building responsibility) were not included in the overall speed calculations. For mean speeds and associated uncertainties, the mean values are calculated using a harmonic mean (which accounts for occupants in different stairs and starting at different floors, each traveling over a fixed distance) rather than a simple arithmetic mean[14]. Appendix B includes details of the calculation of mean speeds and their associated uncertainties.

Local speeds typically represent the speeds of evacuees between "exit" points designated in successive camera views. Where cameras were placed on every floor, the distance between *exit* points included two flights of steps and two landings. Where cameras were placed farther apart, the distance used for the local speed calculation was greater. Since each *exit* point denotes the beginning of a floor, each local speed represents the travel between floors. These speeds were typically calculated by dividing the stair distance between two adjacent *exit* points by the travel time between these points.

For example, in Figure 4, occupants exit the camera view 2 steps down from the landing. Assuming the lower floor has the same arrangement and assuming 10 step per flight and 2 flights per floor, the travel time and distance would be along 40 steps (8 + 10 + 10 + 10 + 2) plus 4 landings.

4.1.5 Density

Density was estimated (in persons/m^2) from camera views of the stair landings. With more than 22000 individual observations of an occupant on a landing, it was impractical to manually count other evacuees nearby an evacuee of interest. Thus, a specific algorithm was defined to represent a consistent calculation of density.

As each occupant entered a camera view, there may have been a number of occupants on the landing in front of the occupant potentially impacting the speed of stair movement. To estimate

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[14] As an example, consider an occupant that travels three consecutive 10 m sections in 10 s, 15 s, and 20 s (thus with local speeds of 1.00 m/s, 0.67 m/s, and 0.5 m/s, respectively). The arithmetic mean of the three local speeds is 0.72 m/s. However, the overall mean speed considering the total distance and time travelled is 30 m / 45 s or 0.67 m/s, which is the harmonic mean of the local speeds. Appendix B includes additional examples and details of the calculation of the harmonic mean speed and the associated uncertainties.

the density on each landing as each occupant entered the landing, the number of other occupants (O_J) in front of the selected occupant (O_I) was determined according to the following:

1. For occupant O_I, count only those occupants, O_J, such that the times, t, are such that $t_{exit,I} \geq t_{exit,J}$ (here we assume that occupants who leave the landing before an occupant arrives are only indirectly impacting the occupant entering the landing by slowing the other occupants still on the landing), and
2. Only those occupants, O_J, such that $t_{enter,I} \leq t_{exit,J} \leq t_{exit,I}$ (only those who leave the landing while occupant I is on the landing) are counted. This discounts occupants who remain on a landing for extended periods of time standing out of the general flow of occupants down the stair. For Buildings 9 and 10, where the majority of the populations were persons with mobility impairments, all occupants were included in the density calculations since they routinely spend considerable time on each landing.

Clearly, these are simplifying assumptions since density is a continuous function at all locations in a stair, including those not directly monitored by cameras. For example, a backup of evacuees on the stairs after a landing will impact the number of people waiting on the landing and thus the density on the landing. In addition, density is inherently a local function so there may be higher or lower densities at positions not monitored by cameras. It is also worth noting that with this definition, it is possible to have a density of zero since the density count does not include the occupant being considered since, in effect, the counted density is the density that the occupant sees as he/she enters the landing. Overall, it is important to recognize the limitations of calculating densities, however the count is conducted.

The area of landings used by occupants is also part of the density calculation. Consistent with the calculation of travel distance on a landing, the effective landing area is calculated using distances from eq. (4) with the inside and outside of the stair forming an inner arc and outer arc of the landing area.

$$A_L = \frac{\pi}{2}\left(\left(w-\delta_o\right)^2 - \delta_i\right) \tag{5}$$

Where w is the stair width, δ_o is the boundary layer applied to the outer lane of the stair and δ_i is the boundary layer applied to the inner lane of the stair. Reference [68] includes additional details of this calculation.

4.2 Summary of Data Collected

A visual distribution of the 30 stairwells can be seen in Figure 5. The number of evacuees in each stair ranged from 12 to 676, with a total of 5249 occupants observed. Buildings 9 and 10 housed elderly as well as disabled occupants, whereas the remaining twelve buildings contained a large majority of those without any mobility impairments. Data from stairwell 2N and 10-3 were excluded from the results and analysis section because they both have a sample size of no more than five evacuees. In addition, the evacuees travelled only a single floor in these stairwells, further limiting the usefulness of the data. Stairwell 12B, which had a sample of twelve participants, is kept because evacuees travelled from multiple floors in the building.

Table 5 presents the descriptive statistics of pre-observation delay, overall speed, and peak density for all 30 stairwells sampled[15]. Occupants moved into the stairwell after a mean delay of 230 s ± 53 s. Pre-observation delay ranges widely from 41 s to 1708 s. Occupants had a mean total evacuation time of 414 s ± 55 s, ranging from 99 s to 1787 s. Participants travelled at overall speeds ranging from 0.07 m/s to 1.7 m/s, with a mean speed of 0.44 m/s ± 0.19 m/s. The mean peak density within the stairwells ranged from 0.00 persons/m^2 to 3.23 persons/m^2, with a mean of 1.87 persons/m^2 ± 0.16 persons/m^2.

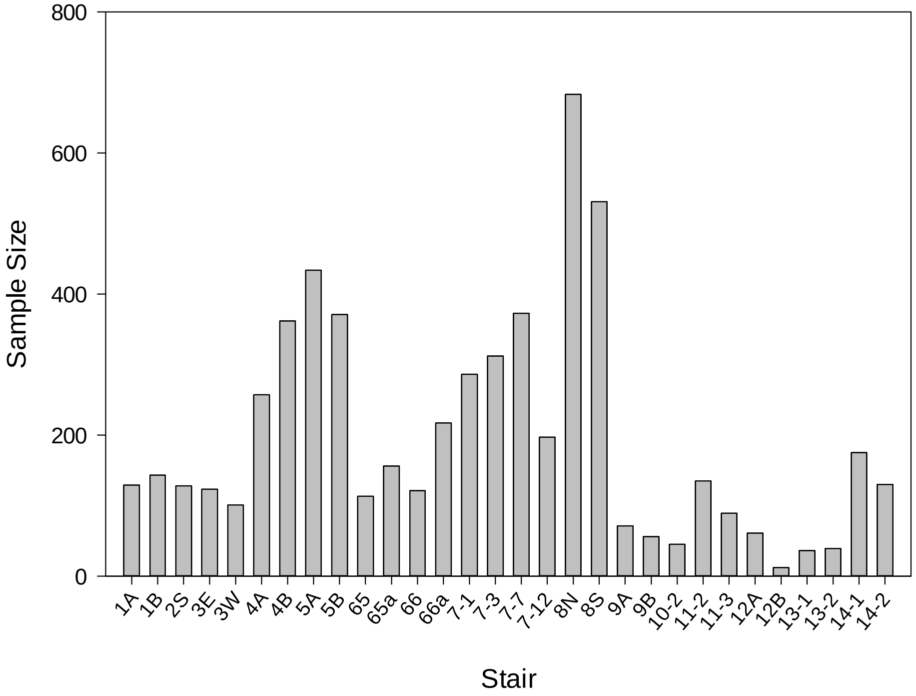

Figure 5. Sample size in each stairwell included in the analysis.

Table 5. Overall Results for Occupant Evacuation in 30 Stairs

Overall				
Variable	**Sample Size**[a]	**Mean**	**Median**	**Range**
Pre-observation delay time (s)	5249	230 ± 53	170	41-1708
Overall Speed (m/s)	5244	0.44 ± 0.19	0.47	0.07-1.7
Peak Density (persons/m^2)	21303	1.87 ± 0.16	2.04	0.00-3.23[16]

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[15] It is standard to describe any distribution with at least two statistics, the distribution mean and the distribution standard deviation, which can be estimated from sample data. In Table 5 and in the text, we describe the sample distributions with the compact notation of the sample mean plus or minus one sample standard deviation. For example, the distribution of mean speeds is 0.44 m/s ± 0.19 m/s. This describes the distribution used to generate a randomly selected evacuee's mean speed. Using the central limit theory, we can calculate a measurement uncertainty for the estimate of the distribution mean. For the mean speed, this uncertainty is ±0.003 m/s, which is less than the error due to rounding and largely a factor of the large sample size. Unfortunately there is not a standard estimate of the uncertainty of estimates of the standard deviation of the distribution. Appendix B details the calculation of mean movement speed and its associated uncertainty.

[16] Note from Section 4.1.5, that a density of zero simply implies that no one was on the landing when an occupant reached the landing on their descent down the stairs.

a – Pre-observation delay includes all occupants who entered the stairs. Overall speed includes occupants who were seen on more than one camera in a stair. Peak density includes all occupants who entered and left one or more landings in a stair.

Table 6 displays the results with respect to stairwells that contain occupants with mobility-impairments (Buildings 9 and 10, a total of three stairs) and those without (the remaining 27 stairs). Those with mobility impairments had a mean pre-observation delay of 160 s ± 11 s, ranging from 41 s to 255 s. Facilities that housed the mobility impaired have considerably larger pre-observation delay and total evacuation time means, as well as variances. Occupants initiated evacuation after a mean of 850 s ± 430 s. The range encompassed a wider amount of times, from 398 s to 1708 s.

Those without mobility impairments maintained a mean overall speed at 0.44 m/s ± 0.18 m/s, which ranged from 0.08 m/s to 1.7 m/s. The mean pace in mobility impaired stairwells decreases to 0.28 m/s ± 0.17 m/s. The range incorporates slower speeds from 0.07 m/s to 0.94 m/s. Mean peak density within the able-bodied stairwells varied from 0.00 persons/m^2 to 3.23 persons/m^2, with a mean of 2.05 persons/m^2 ± 0.13 persons/m^2. Stairwells with mobility-impaired evacuees have a lower mean peak density, 0.25 persons/m^2 ± 0.12 persons/m^2, with the range curtailed at higher values, 0.00 persons/m^2 to 0.39 persons/m^2.

Table 6. Results for occupant evacuation in 30 stairs divided between able-bodied and mobility-impaired evacuees

Stairwells with Primarily Able-Bodied Evacuees (All Buildings Except 9 and 10)

Variable	Sample Size[a]	Mean	Median	Range
Pre-observation delay time (s)	5074	160 ± 11	160	41-255
Overall Speed (m/s)	5074	0.45 ± 0.18	0.54	0.08-1.7
Peak Density (persons/m^2)	20767	2.05 ± 0.13	2.18	0.00-3.23

Stairwells with Primarily Mobility-Impaired Evacuees (Buildings 9 and 10)

Variable	Sample Size[a]	Mean	Median	Range
Pre-observation delay time (s)	170	850 ± 430	440	398-1708
Overall Speed (m/s)	170	0.28 ± 0.17	0.27	0.07-0.94
Peak Density (persons/m^2)	536	0.25 ± 0.12	0.35	0.00-0.39

a – Pre-observation delay includes all occupants who entered the stairs. Overall speed includes occupants who were seen on more than one camera in a stair. Peak density includes all occupants who entered and left one or more landings in a stair.

4.3 Pre-Observation Delay Time

As mentioned earlier, pre-evacuation delay is the time it takes an occupant to initiate evacuation. In these observations, an occupant's delay is operationalized as the length of time from the beginning of the drill until he or she is seen entering the stairwell for evacuation. For this report, this is termed pre-observation delay time. It is important to note that this definition may be different from the more specific pre-evacuation time which may not include travel time from an occupant's original location in the building to the stairwell to begin evacuation.

Figure 6, below, shows the median, interquartile range, 10th and 90th percentile of data, and each outlier for pre-observation delay for the 30 stairwells in this project. The median, represented by the black line, is encased around the middle 50 % of the data with the whiskers signifying the 10th and 90th percentile. The red circles denote outliers in the stairwell with the transparency set to 75 %, in order to see where they tend to accumulate.

Across 30 stairwells, the mean pre-observation delay of occupants is 230 s ± 53 s. Participants in able-bodied buildings have a mean time of 160 s ± 11 s before evacuating into the stairwell. The lowest delays occur in building 12, with stairwell 12A occupants initiating evacuation after 35 s and 12B after 34 s. The quick pace could be attributed to low overall building population and building height as well as pre-announced evacuations. Stairwells with mobility-impaired occupants began to evacuate after a longer period of time, 850 s ± 430 s. These facilities most likely have higher delays than stairwells with able-bodied occupants, having to wait for fire fighter rescue. Building 10 evacuees have the longest mean pre-observation delay at 1660 s. The extensive delay within the assisted living facility can be explained by the placement of several participants in stair descent devices before evacuation. Firefighters who assisted evacuees often had to spend additional time setting up the device and ensuring that the occupant was safe and comfortable.

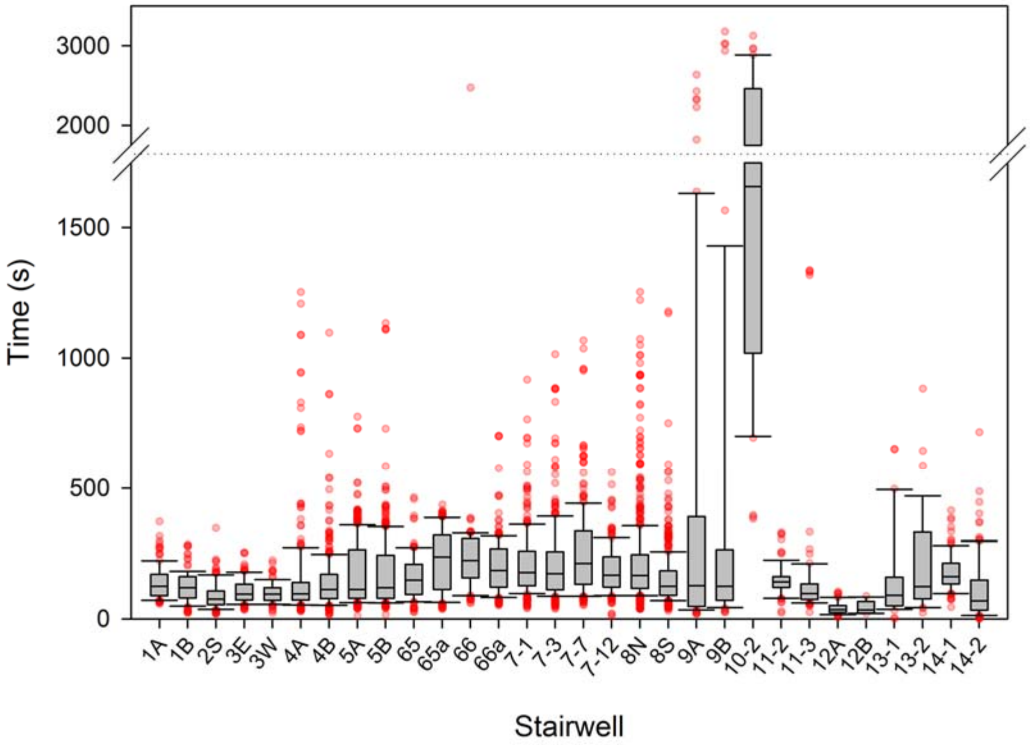
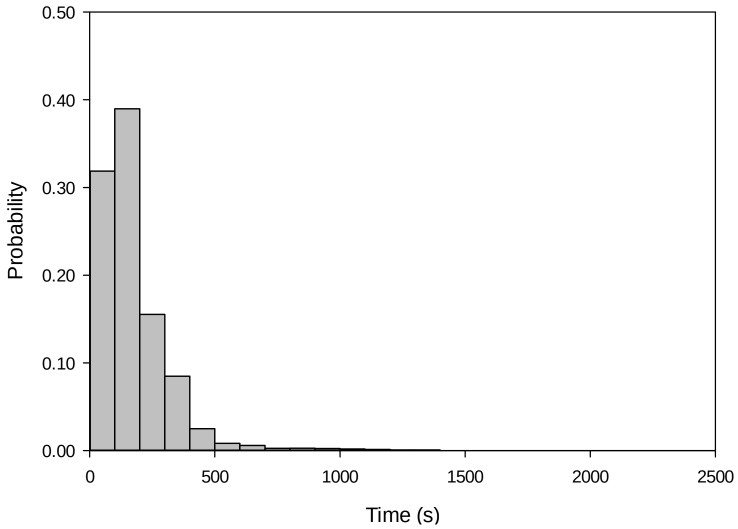
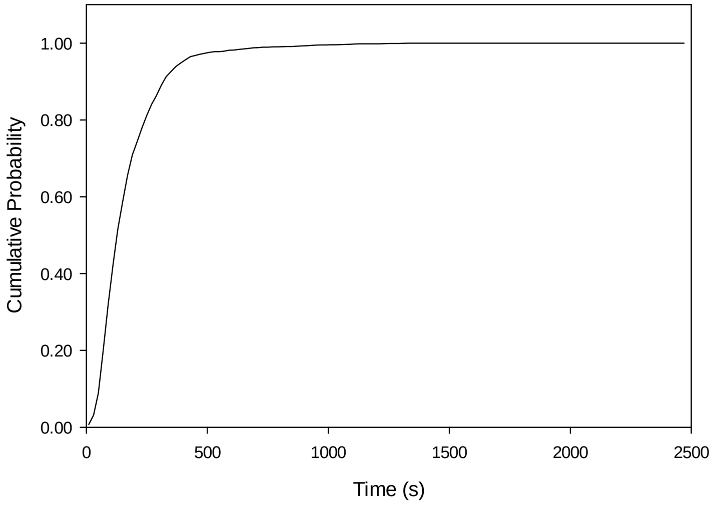


Figure 6. Pre-stairwell evacuation delay time during fire drill evacuations in 14 buildings. The median, represented by the black line, is encased around the middle 50 % of the data with the whiskers signifying the 10th and 90th percentile. The red circles denote outliers.

Probability density plots and cumulative distribution plots, such as those shown in Figure 7 and Figure 8, represent a compilation of all individual pre-observation data from the stairwells analyzed[17].



(a) Probability



(b) Cumulative Probability

Figure 7. Distribution of pre-observation delay in stair evacuations with able-bodied occupants.

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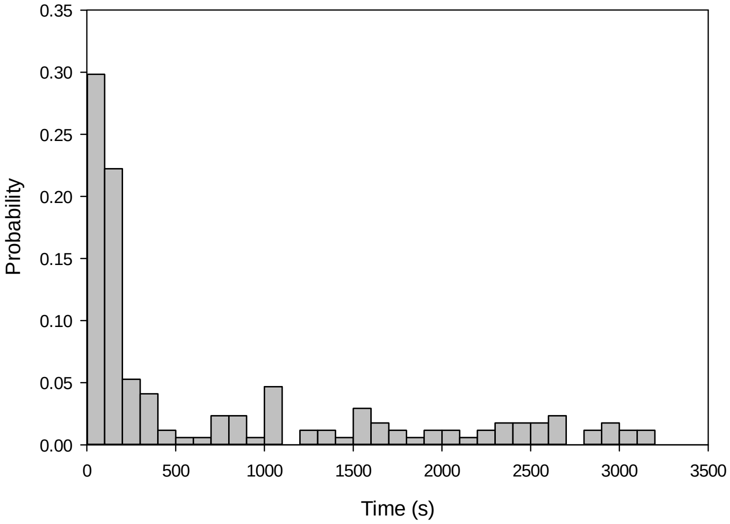
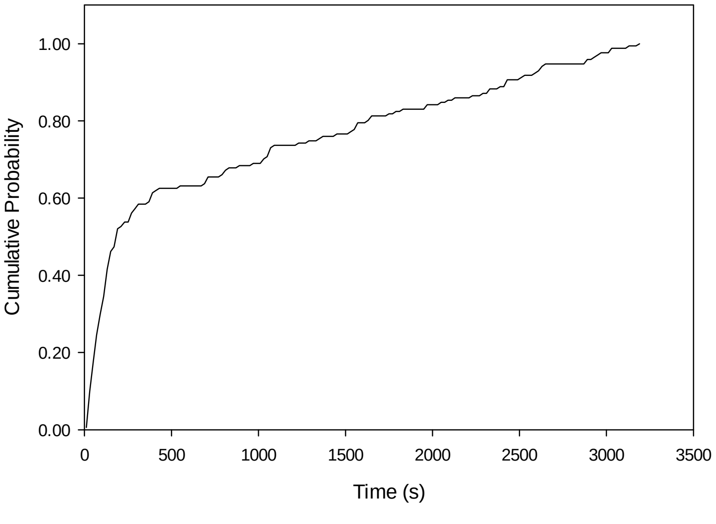
[17] The probability density plot shows the likelihood of the variable of interest, for any participant, to be a specific value. The graph displays the most typical range of values that an occupant would have. The cumulative distribution plot displays the summed probability, and shows the value that a variable observed will probably have before plateauing off, suggesting outliers beyond that range.

Figure 7a and Figure 7b are the pre-evacuation delay probability density and cumulative density plots, respectively, for the stairwells with primarily able-bodied evacuees (all buildings except buildings 9 and 10). The most probable pre-observation delay time in these buildings occurs between 100 s and 200 s, with a probability of 0.39. This statistic encompasses the able-bodied pre-observation delay per stairwell, 160 s ± 11 s, as well as 15 of the 27 individual stairwell medians. The cumulative distribution plot shows that about 97 % of the data will most likely occur before 500 s.



(a) Probability



(b) Cumulative Probability

Figure 8. Distribution of residential pre-observation delay time in building fire drill evacuations with mobility-impaired occupants.

Figure 8 represents a compilation of all individual pre-observation delay data from the stairwells with mobility-impaired evacuees (the 3 stairwells in buildings 9 and 10). The most probable pre-observation time occurs between 0 s and 100 s, with a probability of 0.30. This statistic fails to include any individual residential stairwell mean or even the mobility-impaired pre-observation delay mean, 850 s ± 430 s. The lack of data for mobility impaired evacuees paired with many outliers most likely explain why the measures of central tendency do not overlap with the most probabilistic range of data points. The cumulative distribution plot displays that approximately 52 % of the data will occur earlier than 200 s, before widely scattering throughout the 200 s to 3200 s range.

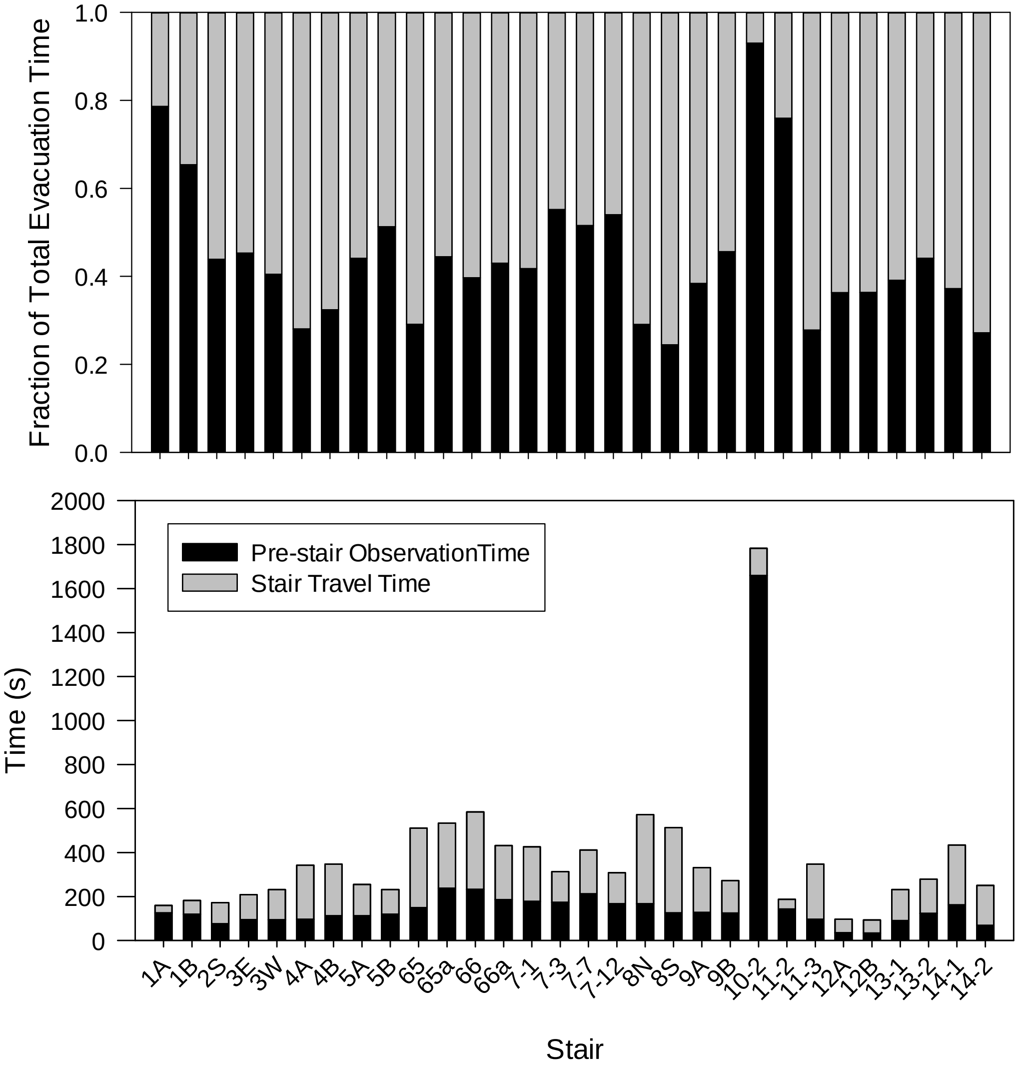


Figure 9. Comparison of mean (median) pre-stairwell evacuation time and stairwell travel time for 14 building fire drill evacuations.

Figure 9 shows a comparison of pre-observation delay and travel time for each stairwell, which make up the total evacuation time (as a fraction of total evacuation time, top, and expressed as time, bottom). Pre-observation delay comprises a median value of 42 % relative an individual's total evacuation time. In the assisted living facility, building 10, pre-observation time exceeds the travel time, constituting an average of more than 90 % of the total evacuation time.

Figure 10 compares pre-observation time with total travel time. The data are compiled in pairs, with an occupant's pre-stairwell evacuation delay (t_{pre}) plotted against his or her total evacuation time (t_{total}). The regression predicts total evacuation time with a strong positive correlation of r = 0.75 and explains 56 % of the total evacuation time variance.

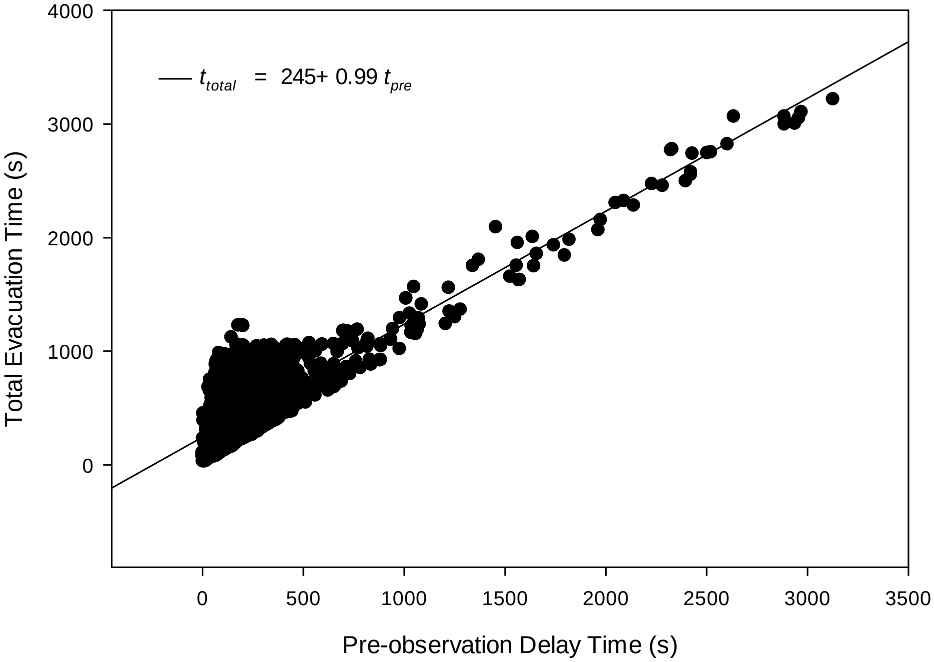


Figure 10. Comparison of pre-observation delay with total evacuation time for 14 building fire drill evacuations.

Another scatterplot (Figure 11) displays the linear regression of travel time versus total evacuation time. Again, the data are compiled in pairs, with an occupant's travel time (t_{travel}) plotted against his or her total evacuation time (t_{total}). The purpose of this graph is to emphasize the effect pre-observation delay has on total evacuation time relative to travel time. The regression predicts total evacuation time with a correlation of r = 0.66, and explains 43 % of the variance in total evacuation time.

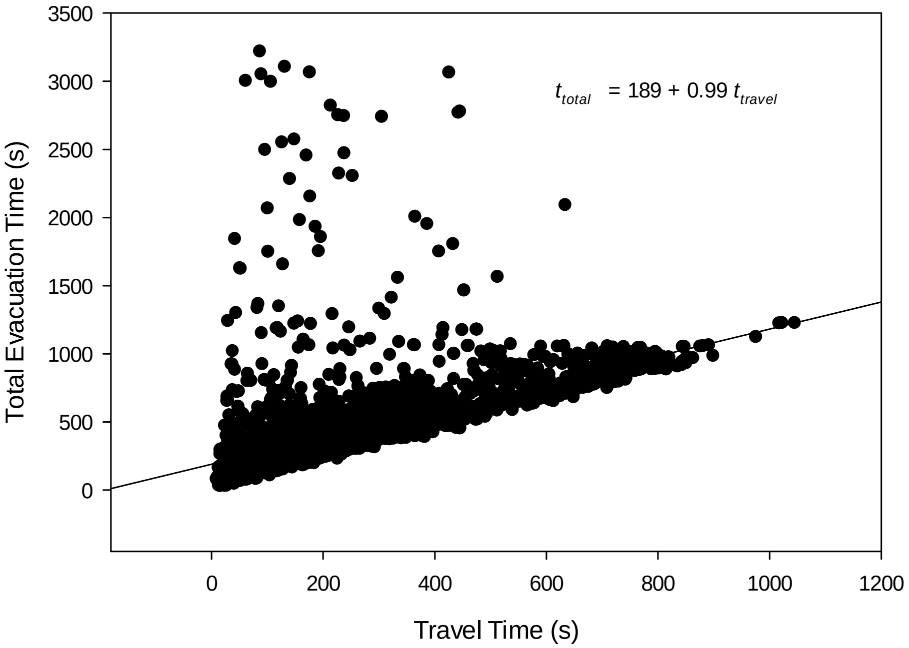


Figure 11. Comparison of travel time with total evacuation time for 14 building fire drill evacuations.

Presumably, travel time should constitute the majority of the total evacuation time since the most distance is traveled during that period, while very little is travelled during the initial evacuation delay period. However, pre-observation delay constitutes a significant fraction of an occupant's total evacuation time and thus influences the total evacuation time. Both community disaster and building fire evacuation research provides evidence that people do not immediately react to verbal warnings or physical cues [69]. Instead, in order to assess and confirm the initial cues, people delay their attempts to take a protective action [69]. The research also shows that characteristics of the crisis situation and of the people who experience the event influence how long an occupant delays before beginning protective action, such as evacuation. Although pre-observation delay consistently seems to occupy much of the total evacuation time, it also has a large variability, likely with a more varied set of activities than stair movement. When pre-observation delay combines with travel time to form the total evacuation time, variability drops.

The high internal variability of pre-observation delay as well as its overwhelming composition of total evacuation time suggest that further research is needed in this area. Future research should focus on the behaviors and environment of the occupants before preparing evacuation movement begins.

4.4 Movement Speeds

In this section, both overall movement speeds of occupants descending the stairwells as well as local speeds throughout the stairwells are considered. Overall speeds are determined from the total time it takes the occupant to evacuate and the distance traveled during that span. Local speeds are the speeds of individuals between cameras views.

4.4.1 Overall Movement Speeds

The mean overall speed of occupants is 0.44 m/s ± 0.19 m/s, across all 30 stairwells. Figure 12 displays both the overall mean and mean local movement speeds for each stairwell[18]. Results show lower variance for overall speeds in comparison to pre-observation delay. This category also contains the highest movement speed from stairwell 12B at 1.7 m/s, possibly due to the low population density[19]. Mobility-impaired occupants move significantly slower in comparison to able-bodied with a mean speed of 0.28 m/s ± 0.17 m/s. Similar to pre-observation delay, mobility-impaired stairwells stray from the rest of the data with slower overall mean speeds.

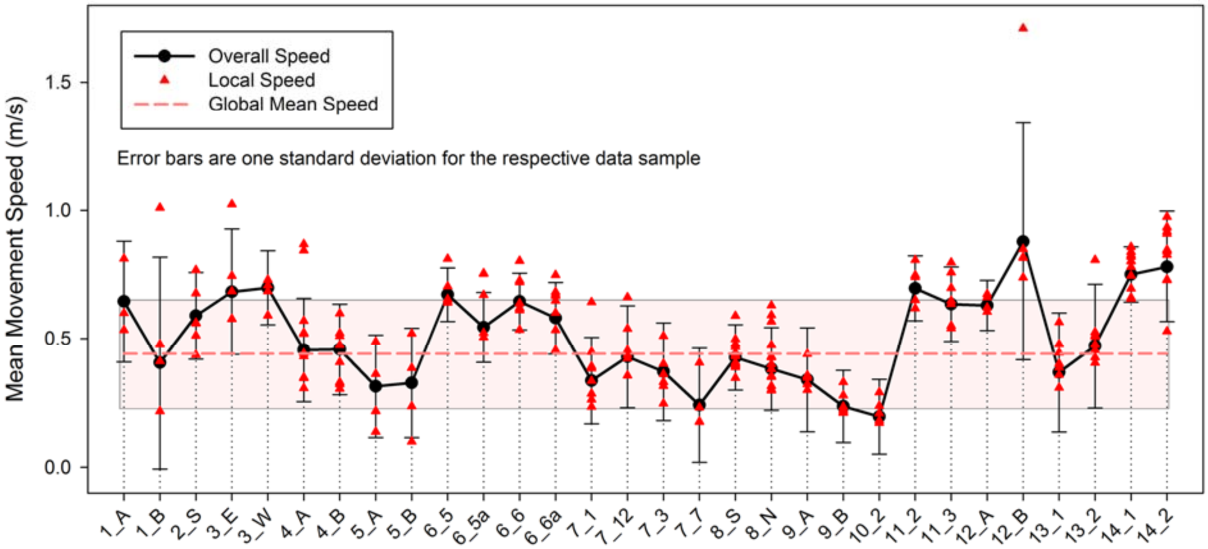


Figure 12. Stair travel speeds in 14 building fire drill evacuations. Shaded area represents the overall mean speed and standard deviation for all 30 stairs.

The mean overall speed across all stairwells, 0.44 m/s ± 0.19 m/s, overlaps with many of the movement speeds found in previous studies. The mean speed found in this study is similar to all ages of occupants' speed found in Lord et al.'s study [2], the optimum condition found in Fruin [37], from Pauls' [57], the recommended speed in Melinik and Booth [70], and with the non-disabled evacuees in Boyce Shields, and Silcock [45]. The ranges from these several studies also encompass NIST's overall mean speed: Pauls and Jones [28], Pauls [57], the WTC Towers in Galea [26], Wayguidance in Wright, Cook, and Webber [46], and all of Lee and Lam's [39].

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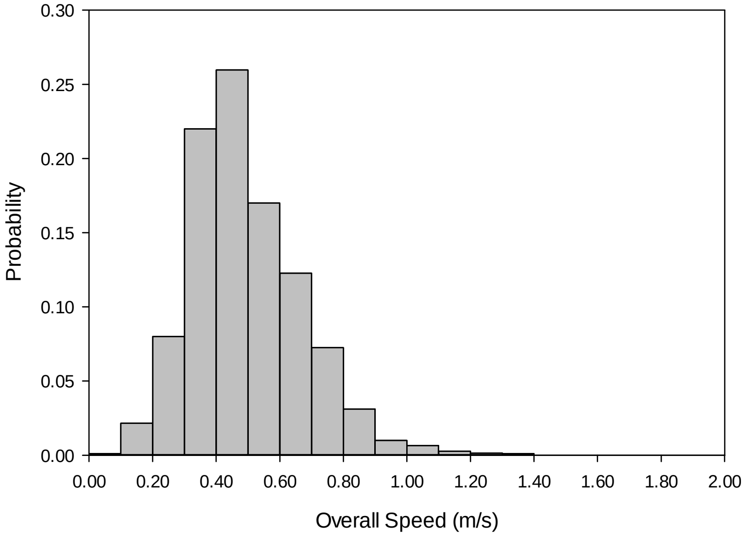
[18] Overall speed is taken from where an evacuee first entered the stairwell until they left the stair at the exit. Local speed is taken between successive camera locations within a stair so there are typically multiple local speeds for each evacuee.

[19] Although this high value is well above typical movement speeds in stairwells and is certainly an outlier in the data, the high uncertainty in Stair 12B means that it is still within 2 standard deviations and was kept in the data set. Without this value, the highest local speed is about 1 m/s.

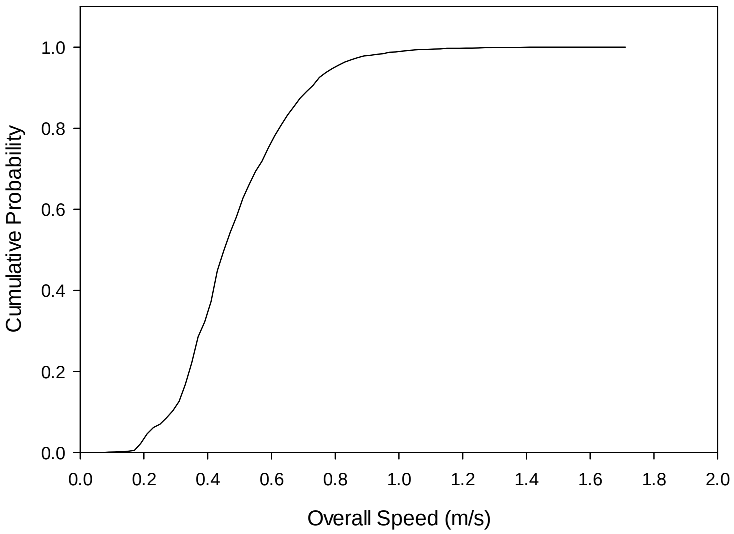
The mean overall speed in mobility-impaired buildings, 0.28 m/s ± 0.17 m/s, coincides with the disabled occupants' speeds from various, from Lord et al. [2], Boyce Shields and Silcock's [45] study on locomotion disability as well as Proulx's [13, 14] studies on occupants with mobility impairments. Additionally, these speeds from mobility impaired research coincide with all of the assisted living facilities' (buildings 9 and 10) speeds in the individual stairwells (see section 5.2). The consistency found between these studies enhances the credibility of the current results.

The current study includes sufficient data to understand the distribution of movement speeds beyond mean speeds available in the literature and allows comparison with previous results. The probability and cumulative probability in Figure 13 represent a compilation of each evacuee's overall speed across all the buildings without mobility impairments. There was a 26 % probability that an occupant evacuated with an overall speed between 0.40 m/s and 0.50 m/s, which encompasses 9 of the 27 stairwell medians. Results tend to accumulate around the highest probability segment, from 0.30 m/s to 0.60 m/s, which encompasses 16 of 27 of the stairwell medians as well as the mean able-bodied speed, 0.44 m/s ± 0.17 m/s. This range implies there is a 65 % probability that an able-bodied occupant's speed was between 0.30 m/s to 0.60 m/s. The cumulative distribution plot shows that an overall speed of 0.81 m/s or less captures approximately 96 % of the occupants travel speed. Stairwell 12B and 14-2 reside within the plateau and could be outliers.

The probability density plot and cumulative distribution plot in Figure 14a and Figure 14b represent a compilation of each evacuee's overall speed across buildings with primarily mobility-impaired occupants. 30 % of the occupants evacuated with an overall speed between 0.20 m/s and 0.30 m/s. This probability segment encompasses the mean mobility-impaired speed, 0.28 m/s ± 0.17 m/s, as well as 2 of the 3 individual stairwells medians. The cumulative distribution plot shows that an overall speed of 0.68 m/s or less captures approximately 96 % of the occupants travel speed.

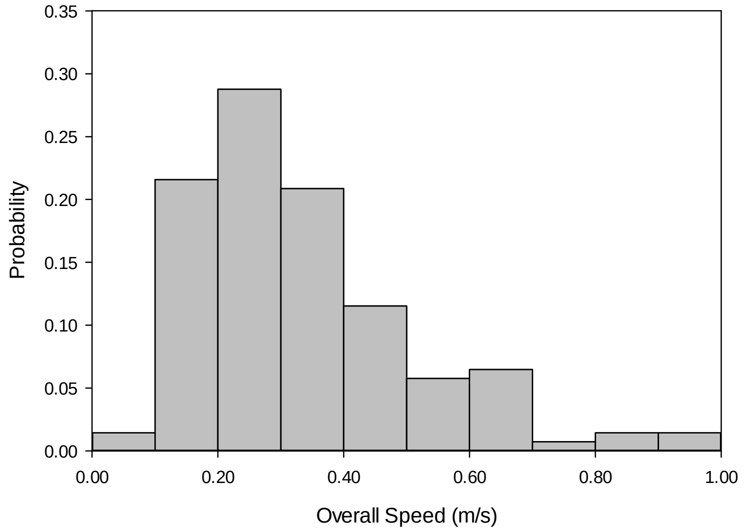


(a) Probability

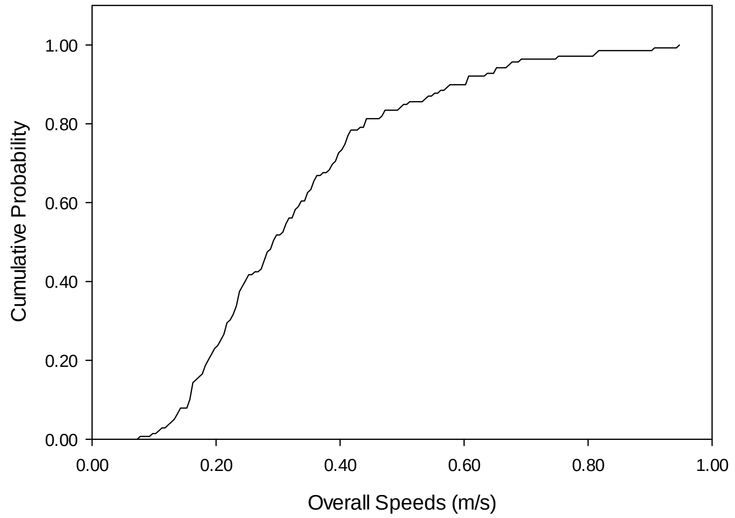


(c) Cumulative Probability

Figure 13. Distribution of stair movement speeds in buildings fire drill evacuations with able-bodied occupants.



(a) Probability



(b) Cumulative Probability

Figure 14. Distribution of stair movement speeds in building fire drill evacuations with mobility-impaired occupants.

4.4.2 Local Movement Speeds

Local speeds were analyzed at each camera location. Due to limited resources, camera placement varied and only selected floors could be observed, which limited the analysis of local speeds. Possible effects of speed changes from descending the stairwell, such as increasing density and fatigue, could be discerned by examining these speeds. However, all floor distributions are skewed, and rarely show a predictable pattern. The mean local speeds vary widely within and among stairwells from 0.10 m/s ± 0.008 m/s to 1.7 m/s ± 0.13 m/s. Figure 12 summarizes the local speeds compared the overall means presented earlier. Additional details of local speeds are presented in depth in Appendix C to illustrate the high variability within and between floors.

5 Discussion and Analysis

Occupant movement on stairs has typically been described by measurable geometric parameters describing the design of the stairs. For example, the SFPE Handbook [59] includes a correlation in terms of a power law fit to the total population and effective stair width:

$$0.206\left(\frac{P_{total}}{w_{eff}}\right)^{0.27} = \frac{F_{avg}}{w_{eff}} \tag{6}$$

where F_{avg} is the mean flow of occupants down the stairs, P_{total} is the population using the stairs, and w_{eff} is the effective width of the stairs. Similarly, flow is correlated to the density of occupants in the stairs [59]:

$$F_{avg} = 1.26D - 0.33D^2 \tag{7}$$

where D is the density of occupants on the stairs in persons/m^2.

This section provides analyses of the results presented in the previous chapter in terms of these and additional stair design parameters to understand their relative importance to occupant speed (sections 5.1 and 5.2), flow (section 5.3), and occupant interaction/crowding (sections 5.4 and 5.5) during stair evacuation. Finally, an example of the use of the data for egress modeling is presented (section 5.6).

5.1 Comparison of Speed and Density Results with Literature Values

Table 7 summarizes the overall pre-observation times and stair movement speeds from this study. Overall speeds varied from 0.07 m/s to 1.7 m/s with a mean of 0.44 m/s ± 0.19 m/s. The range encompassing observations in this study overlaps with the movement speeds found in previous studies. The overall speed for all 14 buildings is similar to the able-bodied occupant speed found in previous studies (see, for example, reference [3]).

Table 7. Summary of travel times, overall speeds, and peak density during stair evacuations in 14 buildings.

Variable	Sample Size[a]	Mean ± Std. Error	Median
Pre-observation delay time (s)	5249	230 ± 53	170
Overall Speed (m/s)	5244	0.44 ± 0.19	0.47
Peak Density (persons/m^2)	21303	1.87 ± 0.16	2.04

a – Pre-observation delay includes all occupants who entered the stairs. Overall speed includes occupants who were seen on more than one camera in a stair. Peak density includes all occupants who entered and left one or more landings in a stair.

Overall speeds in each stair fell within one standard deviation of the global mean for the current study, except for stair 10-2, an assisted living facility where most occupants were evacuated with the use of stair travel devices.

With the considerable variation in all the available data (as indicated by the standard deviation shown for some of the studies), the newer data are typically within the range of data in the literature and quite similar to the "optimum" or "moderate" movement speed of Fruin [37].

Mean movement speeds in the literature for very dense evacuations (for example, Fruin's crush load [37] and the 9/11 World Trade Center evacuation [9]) are significantly lower than both the current study and mean values from the literature. This may be indicative of the higher occupant densities in the slower stairs.

The results from this study are consistent with previous studies for evacuees specifically identified as needing assistance. The mean speed in the current study, 0.28 m/s ± 0.17 m/s was similar to movement speeds of occupants using canes as with the Boyce, Shields, and Silcock [45] study (0.32 m/s ± 0.12 m/s). For occupants needing assistance, the ranges are also similar with 0.11 m/s to 0.23 m/s for the UK study and 0.11 m/s to 0.33 m/s in the current study. These results contrast to the somewhat faster speeds found in the earlier studies of Fruin [37], Fujiyama and Tyler [47], and Proulx et al. [13, 14].

It is important to recognize that all of these earlier data sets were collected under differing conditions, with a range of building heights (ranging from a few stories to about 30 stories in height), occupant capabilities (two studies looked specifically at occupants with locomotion disabilities), and evacuation conditions (many were fire drills, but actual events are also included). Also noteworthy is that all of these data sets were collected and analyzed with differing definitions of travel distance, movement speed, and occupant density [68].

While the current study does not support recent concerns over slowing evacuation speeds resulting from increased obesity rates and lower fitness levels [71], additional study is needed to better understand the impact of egress from taller buildings, during emergency conditions compared to fire drill evacuations, and accounting for potential differences due to differing techniques used to calculate speed and densities.

5.2 Stairwell Use by People with Disabilities

Although RSET calculations in egress models have been revised to incorporate various behaviors of able-bodied occupants, negligible amounts of egress movement data have been collected for the disabled [72-74]. Two buildings (Buildings 9 and 10) in the current study were occupied exclusively by older adults. Evacuees, whose movements and behavior were analyzed while descending the stairwells, included those visually identified as older as well as individuals needing assistance from canes, walkers, stair travel devices, and/or other people (often staff or firefighters). Due to the lack of data on disabled occupants, this section will explicitly present the overall mean speeds on stairs and local speeds of the residents with various mobility impairments. Additionally, these data will be compared with experimental and evacuation drill results in the literature.

5.2.1 Overall Speeds

Occupants evacuated Buildings 9 and 10 at a mean speed of 0.28 m/s ± 0.17 m/s with a range from 0.07 m/s to 0.94 m/s. All speeds included in Table 8 represent those along the incline of the stair. Table 8 also includes the interquartile range to show the difference between the smallest and largest values in the middle 50 % of the data. The interquartile range provides a simple guide to highlight any significant outliers in the "Range" column.

Here, an occupant assisting and the occupant being assisted are defined as one system, similar to how firefighters helping a disabled occupant in a stair travel device are treated as one unit. Only one occupant helped another evacuee in either of the two drills (with a mean speed of 0.19 m/s). The people assisted by staff members or another occupant evacuated at 0.24 m/s ± 0.13 m/s. Those assisted by firefighters had a mean speed of 0.14 m/s ± 0.05 m/s. Individuals in stair travel devices travelled at a mean speed of 0.20 m/s ± 0.04 m/s. The older population without any disabilities moved faster than the other groups at 0.35 m/s ± 0.17 m/s. Individuals were confirmed as older by additional visual cues such as hair color or gait.

Although the disabled groups shared similar mean speeds, occupants being assisted by firefighters were significantly slower in both buildings (0.14 m/s ± 0.05 m/s). Due to the smaller sample size compared to the total population (8 individuals assisted by firefighters), an evaluation of each evacuee can help to understand why this category had the slowest mean speed of all the data collected. In the 6-story building, delays were associated with firefighters who had to take time assisting the occupants as well as travel up the stairwells with stair travel devices. It should be noted, however, that the limited camera views (only on the landings and only every other floor in the 13-story building) means there could be additional undocumented situations that may have affected the slow speeds.

Table 8. Mean speeds on stairs for all evacuees and within various disability groups. (Uncertainties are one standard deviation from the mean.)

Overall

	Sample size	Mean	Range
Population	170	0.28 ± 0.17	0.07 - 0.94
Cane	18	0.23 ± 0.07	0.12 - 0.34
Assisting/Assisted occupant	14	0.24 ± 0.13	0.08 - 0.54
Assisted by fire fighter	8	0.14 ± 0.05	0.07 - 0.22
Stair travel device	34	0.20 ± 0.04	0.11 - 0.29
Older adults, no assistance[a]	90	0.35 ± 0.17	0.14 - 0.94

Building 9

	Sample size	Mean	Range
Population	125	0.30 ± 0.18	0.12 - 0.94
Cane	14	0.23 ± 0.08	0.12 - 0.34
Assisting/Assisted occupant	7	0.27 ± 0.11	0.17 - 0.43
Assisted by fire fighter	3	0.17 ± 0.05	0.14 - 0.22
Stair travel device	14	0.21 ± 0.04	0.15 - 0.28
Older adults, no assistance[a]	81	0.36 ± 0.17	0.15 - 0.94

Building 10

	Sample size	Mean	Range
Population	45	0.20 ± 0.10	0.07 - 0.54
Cane	4	0.22 ± 0.08	0.15 - 0.31
Assisting/Assisted occupant	7	0.17 ± 0.17	0.08 - 0.54
Assisted by fire fighter	5	0.11 ± 0.04	0.07 - 0.15
Stair travel device	20	0.20 ± 0.04	0.11 - 0.29
Older adults, no assistance[a]	9	0.23 ± 0.14	0.14 - 0.46

a – Since both buildings were specifically identified as housing for older adults, the current study identified those not needing assistance by a process of elimination (i.e., no assistance from canes, stair travel devices, or other people).

5.2.2 Stair Travel Device Use

During the drills, video cameras captured the evacuation of 34 residents in stair travel devices. Overall speeds using stair travel devices were similar in both buildings: 0.21 m/s ± 0.04 m/s in

Building 9 and 0.20 m/s ± 0.04 m/s in Building 10. From video footage analysis, NIST recognized five prominent methods firefighters used to assist residents in stair travel devices down the stairwells. These methods are listed here as:

- One firefighter was stationed in front of the resident in the chair guiding the chair down using the front handles, and one firefighter was behind the chair pushing it down the stairs. (1 FF front, 1 FF back)
- Two firefighters were stationed in front of the resident in the chair guiding the chair down using the front handles (or sometimes one was stationed on the side of the chair), and one firefighter was behind the chair pushing it down the stairs. (2 FF front, 1 FF back)
- One firefighter was stationed in front of the resident in the chair guiding the chair down using the front handles, and one firefighter was behind the chair pushing it down the stairs. Also, one firefighter was following behind the group carrying or dragging a wheelchair or walker equipment that likely belonged to the resident. (1 FF front, 1 FF back, 1 FF walker)
- One firefighter was stationed in front of the resident in the chair guiding the chair down using the front handles, and one firefighter was behind the chair pushing it down the stairs. Also, one firefighter was following behind the group without any equipment in hand (1 FF front, 1 FF back, 1 FF watching).
- One firefighter was stationed in front of the resident in the chair guiding the chair down using the front handles, and one firefighter was behind the chair pushing it down the stairs. Also, there is a combination of a firefighter watching the group without any equipment as well as another carrying or dragging a wheelchair or walker (1 FF front, 1 FF back, FF combination).

Table 9. Overall speeds on stairways for evacuees on stair travel devices from Buildings 9 and 10.

	Overall		Building 9		Building 10	
	Sample Size	Mean	Sample Size	Mean	Sample Size	Mean
Population	34		14		20	
1 FF front, 1 FF back	18	0.19 ± 0.04	11	0.20 ± 0.03	7	0.18 ± 0.04
2 FF front, 1 FF back	2	0.21 ± 0.01	-	-	2	0.21 ± 0.01
1 FF front, 1 FF back, 1 FF walker	7	0.23 ± 0.03	2	0.25 ± 0.03	5	0.23 ± 0.02
1 FF Front, 1 FF back, 1 FF watching	2	0.19 ± 0.04	-	-	2	0.19 ± 0.04
1 FF front, 1ff back, FF combination	5	0.26 ± 0.05	1	0.24 -	4	0.25 ± 0.06

a – Overall sample size reflects additional stair travel devices where more than one individual method was observed and thus may not equal the sum of individual method counts

Table 9 shows the distribution of the method by which stair travel devices were used in each building, with accompanying movement speeds on stairs. There was no single technique used by participating fire department companies to operate the stair travel devices; however, the primary method positioned one firefighter in front to guide the chair and another in the back to push the chair. This particular method may provide the most efficient evacuation for a building because it reduces the number of firefighters assisting a resident while maintaining a speed similar to the other movement data collected. Although the quickest method (0.26 m/s ± 0.05 m/s) could be considered a best-case, the number of people involved in that system (at least 3) could cause unnecessary congestion and fewer firefighters to help other occupants reach safety. The speed was also largely driven by a small number of faster evacuees.

5.2.3 Comparison to Previous Studies

Previous research findings (shown in Table 2) can also be compared to results from the current study. The majority of literature examined presents observations of unassisted movement speeds of older adults on stairways. The current study found that older occupants in the two buildings traveled on 170 mm (6.5 in) rise and 300 mm (12 in) stairs at a rate of 0.35 m/s ± 0.17 m/s. These findings contrast to the slightly faster speeds found in the earlier studies of Fruin [37], Fujiyama and Tyler [47], and Proulx et al. [3]. Fruin [37] found mean speeds of 0.67 m/s for men and 0.63 m/s for women (both over 50 years old) on similar stair configurations. Fujiyama and Tyler [47] observed speeds of 0.88 m/s ± 0.17 m/s for occupants (60 to 81) years old on similarly configured stairs as well. Proulx et al. [3] observed speeds of 0.57 m/s and 0.58 m/s for occupants over 65 years old from two residential buildings.

There are three main reasons why the current study observed slower movement speeds on stairs. First, as noted above, one of the buildings in the current study was an assisted-living facility. The second building was simply designated as housing for older adults. This study was thus able to observe occupants evacuating with a wide range of disabilities, which may otherwise be difficult to capture during evacuation drills from other types of buildings, especially in buildings where disabled occupants may not participate. Secondly, it may be possible that certain older occupants had visually undetectable mobility impairments that slowed them down. Whereas previous experiments could distinguish between mobility-impaired and older participants, the current study identified older individuals by a process of elimination (i.e., no assistance from canes, stair travel devices, or other people). Although the data acquired in this study may not facilitate direct comparison, the authors posit that a situation when all occupants, regardless of disability, must evacuate represents conditions that would likely be found in an actual emergency building evacuation. Finally, the mean values in the current study are calculated differently than those in previous studies, using a harmonic mean (which accounts for occupants in different stairs and starting at different floors traveling different distances) rather than a simple arithmetic mean. The harmonic mean is always smaller than the arithmetic mean.

The results from this study are reasonably consistent with previous studies for evacuees needing assistance. The current study (0.24 m/s ± 0.13 m/s, Table 8), found similar movement speeds of occupants using canes as with the Boyce, Shields, and Silcock [45] study (0.32 m/s ± 0.12 m/s).

Adams and Galea's [75] study presented movement speeds of individuals in stair travel devices. The mean speeds observed across all four types of evacuation devices utilized (Evac+Chair, Carry Chair, stretcher, and Drag Mattress) were faster than those in the current study. The researchers found a mean speed of 0.81 m/s for the Evac+Chair and 0.57 m/s for the carry chair, whereas, this study found occupants evacuating around a fourth of the speed of the Evac+Chair and less than half the speed of the carry chair (0.20 m/s ± 0.04 m/s, Table 8). Such a difference in speeds can be attributed to the variation in data collection methods. Although very little congestion was observed in the current study, occupants were evacuated simultaneously during the evacuation drill; whereas in Adams and Galea's study, occupants were evacuated one team at a time. Another possible reason for differences is the preparation that staff and firefighters had with these chairs. Researchers in the Adams and Galea [75] study observed trained hospital staff familiar with the operation of these devices. However, the current study involved the local fire department that participated in the evacuation drill as part of a training exercise. The firefighters were most likely not as well-versed in the use or manipulation of these chairs as the hospital staff in Adams and Galea's [75] study. Therefore, this study's stair travel device movement data should be used for scenarios when individuals assisting occupants are not well-trained or experienced in the use of the devices.

5.3 Flow on Stairs

As mentioned earlier, one purpose of this report is to provide a better technical foundation for future code requirements for egress stair design. In order to do this, it is essential to understand the factors that most influence various aspects of evacuation time. A building evacuation is dependent on a number of different events and decisions for each person in the building. As shown in Figure 1, there are distinct stages in an evacuation such as the time from the event to the alarm, the time from the alarm to the decision to evacuate, and the travel time. The travel time can be further broken into travel time on the starting floor and travel time in the stairs. In each part of the evacuation process, there are impacts from a number of sources including human behavior, communication, building procedures and physical constraints.

In this section, the factors are identified that influence occupant flow on stairs. The factors that have been identified in the literature as influential to occupant flow are building population [59], stair width [50], stair geometry [50], and overall distance traveled [59]. The analysis in this section explores each of these factors for their contribution to occupant flow.

5.3.1 Early and Late Evacuees

The analysis in this report focuses primarily on the middle 90 % of the evacuees in each stair. Figure 15 shows a sample plot of the number of people that have exited the stair by a given time for a representative stair included in the study. The plot has been divided into three sections. The middle section, which is made up of the 5th percentile to the 95th percentile of the population, can be characterized by a straight line. The slope of this line is equal to the mean flow for the middle 90 % of the evacuating population.

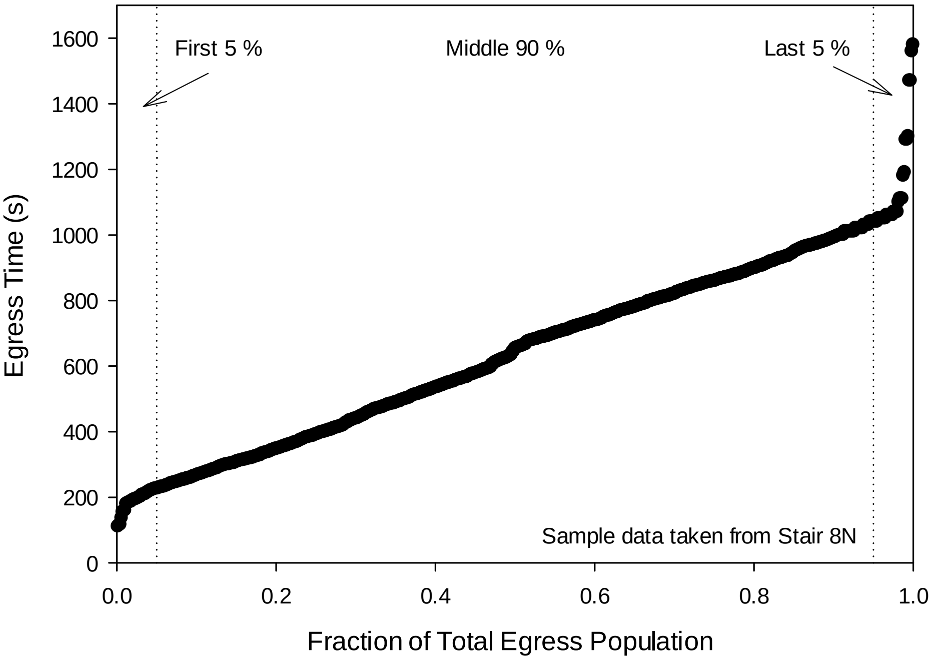


Figure 15. Sample fraction of stair population evacuated as a function of time since building alarm

For the early (the first 5 %) and late (the last 5 %) evacuees, the exit times and thus the flow cannot be reasonably described with a straight line. The flow rate in these sections changes as the egress transitions from no flow to the quasi-steady flow of the middle 90 % in the first section and from quasi-steady flow back to a zero flow condition.

For the early evacuees, evacuation time is largely driven by their time prior to entering the stairs for evacuation. Since these early evacuees also naturally begin on the lower floors of a building, pre-evacuation time is a larger fraction of their total evacuation time.

Most of the late evacuees were those with building duties during the evacuation such as floor wardens (with responsibility to ensure their assigned areas were evacuated prior to beginning their own evacuation) or first responders (with similar responsibilities or who were observing the drill for post-drill assessments). A far smaller fraction either began their evacuations after an extended pre-evacuation delay or in a few cases moved very slowly down the stairs. Both of these are largely addressable by pre-drill training that stresses the need to begin evacuation quickly or ensuring all evacuees understand available options for assisted evacuation. Thus, the overall evacuation time of very late evacuees are largely unaffected by details of stair design and are not considered further in this section. Other aspects of efficient building evacuation including pre-planning, training, or other evacuation strategies which are outside the scope of this report may particularly address the late evacuees.

Still, the time for the early and late evacuees can impact the overall evacuation time for a stair. Table 10 shows the fraction of the total evacuation time it takes for the early and late evacuees. On average, the early and late evacuees each account for about 20 % of the total stair evacuation time with a wide range for both. Thus, estimation of evacuation time must include an initial pre-evacuation time (time taken by the early evacuees to reach the stairwells), the time taken by the bulk of the evacuees (time taken by the middle 90 % in the analysis in this report), and the added evacuation time for late evacuees. For the latter, a design margin is typically included in the estimates.

Table 10. Impact of early and late evacuees on overall evacuation time for the thirty stairs included in the study.

	Fraction of Total Evacuation Time	
	Mean	Range
First 5 %	0.20 ± 0.12	0.03 - 0.46
Last 5 %	0.22 ± 0.18	0.01 - 0.61

5.3.2 Analysis of Flow

Describing occupant egress as a flow is a well-established means of analyzing an evacuation process [37, 41, 58, 76]. Flow is simply the ratio of the number of evacuees passing through a known point in the evacuation path (most typically, the exit door at the bottom of the stair) to the time difference between the first and last evacuees. To estimate the mean flow, we exclude the very early evacuees (the first 5 % of the population) and very late evacuees (the last 5 % of the population) and calculate the mean flow for the middle 90 % as

$$F_{ave} = \frac{P_{5-95}}{t_{95} - t_5} \tag{8}$$

where F_{ave} is the mean flow, $P_{5\text{-}95}$ is the total number of evacuees in the middle 90 % of the population, and finally t_{95} and t_5 are the exit times of the person at the 95th percentile and the person at the 5th percentile, respectively.

In order to understand the relative importance of different factors on stair flow, correlations and functional relationships using both linear least squares (LLS) and the Bayesian parameter estimation approach that is described in Appendix D were considered to better understand the parameters that are important for determination of the flow. In this section, seven different functional relationships between various measured quantities (shown in the models below) and the mean flow of the middle 90 % of non-residential stairs, F_{ave}, were considered. The models that were evaluated are as follows:

Model 1. Flow as a function of total population, P_{total}, power law model,

$$F_{ave} = \theta_0 P_{total}^{\theta_1} \tag{9}$$

Model 2. Flow as a function of exit distance, D_{exit}, power law model,

$$F_{ave} = \theta_0 D_{exit}^{\theta_2} \tag{10}$$

Model 3. Flow as a function of effective width, w_{eff}, power law model,

$$F_{ave} = \theta_0 w_{eff}^{\theta_3} \tag{11}$$

Model 4. Flow as a function of occupants and exit distance,

$$F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2} \tag{12}$$

Model 5. Flow as a function of occupants and effective width,

$$F_{ave} = \theta_0 P_{total}^{\theta_1} w_{eff}^{\theta_3} \tag{13}$$

Model 6. Flow as a function of exit distance and effective width,

$$F_{ave} = \theta_0 D_{exit}^{\theta_2} w_{eff}^{\theta_3} \tag{14}$$

Model 7. Flow as a function of occupants, exit distance, and effective width,

$$F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2} w_{eff}^{\theta_3} \tag{15}$$

Where θ_0, θ_1, θ_2, and θ_3 are constants that will be determined by linear least squares or Bayesian parameter estimation. F_{ave} is the mean flow of the middle 90 % of evacuees using the stair, P_{total} is the total population of evacuees using the stair, D_{exit} is the maximum distance travelled by an evacuee in the stair, w_{eff} is the effective width of the stair. See Appendix D for additional details.

The analyses for all the models followed the same procedure as detailed in Appendix D for model 1. A summary of all the parameter values from both methods for the seven models are found in Table 11. In addition to the overall fit of the equation (where a higher R^2 value or lower deviance information criterion (DIC) value indicates a better fit[20]), the magnitude of each of the four constants, θ_0, θ_1, θ_2, and θ_3, are included along with the 95 % confidence interval for the constants (for the Bayesian analysis) and the p-value (for the LLS analysis). The 95 % confidence interval (95 % CI) and the p-value are indicators of the precision and statistical significance of the constant, respectively.

From Table 11, the trends for the dependency of stair population, exit distance, and effective stair width on flow are consistent for all the models and for both the Bayesian and LLS analyses. Stair population and effective width consistently show a positive correlation (indicated by the sign of the respective constant) with flow (higher population or effective width lead to a higher flow). The exponents for exit distance and number of occupants are nearly identical when each parameter is correlated with mean flow individually or together. Furthermore the R^2 for the two together is actually slightly larger than the sum of the two R^2 individually. From the linear least squares analysis, models that include stair population or exit distance typically show correlations with p-values at the 0.01 or 0.005 level indicating statistically meaningful dependence of flow on these parameters and with fairly consistent magnitudes for these variables.

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[20] R^2, the coefficient of determination is a measure of how well the measured experimental data fit the selected regression model. Values for R^2 range from 0 to 1, with a higher value indicating a better fit. Like R^2, the Bayesian DIC is a measure of the quality of the chosen model, with lower values of the DIC indicating a better fit.

Table 11. Values for 7 models determined using Bayesian inference and linear least squares.

Bayesian Inference Analysis

Model		R²	DIC	Population, θ_1		Exit Distance, θ_2		Effective Width, θ_3		Constant, θ_0	
				θ_1	95 % CI	θ_2	95 % CI	θ_3	95 % CI	θ_0	95 % CI
1	$F_{ave} = \theta_0 P_{total}^{\theta_1}$	0.64	-30	0.34	[0.09, 0.55]					0.08	[0.02, 0.29]
2	$F_{ave} = \theta_0 D_{exit}^{\theta_2}$	0.62	-21			-0.32	[-0.50, -0.16]			2.2	[1.06, 5.23]
3	$F_{ave} = \theta_0 w_{eff}^{\theta_3}$	0.65	-20					1.46	[0.69, 2.27]	0.54	[0.46, 0.62]
4	$F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2}$	0.89	-48	0.38	[0.24, 0.52]	-0.33	[-0.47, -0.23]			0.32	[0.14, 0.77]
5	$F_{ave} = \theta_0 P_{total}^{\theta_1} w_{eff}^{\theta_3}$	0.77	-31	0.22	[0.05, 0.41]			1.23	0.49, 2.03]	0.16	[0.06, 0.41]
6	$F_{ave} = \theta_0 D_{exit}^{\theta_2} w_{eff}^{\theta_3}$	0.69	-23			-0.21	[-0.40, -0.03]	0.75	[-0.23, 1.67]	1.48	[0.64, 3.32]
7	$F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2} w_{eff}^{\theta_3}$	0.91	-48	0.36	[0.23, 0.49]	-0.28	[-0.41, -0.17]	0.49	[-0.09, 1.03]	0.30	[0.14, 0.59]

Linear Least Squares Analysis

Model		R²	Population, θ_1		Exit Distance, θ_2		Effective Width, θ_3		Constant, θ_0	
			θ_1	p-value	θ_2	p-value	θ_3	p-value	θ_0	p-value
1	$F_{ave} = \theta_0 P_{total}^{\theta_1}$	0.64	0.46	0.005					0.037	0.005
2	$F_{ave} = \theta_0 D_{exit}^{\theta_2}$	0.61			-0.4	0.005			3.2	0.020
3	$F_{ave} = \theta_0 w_{eff}^{\theta_3}$	0.62					2.0	0.020	0.54	0.005
4	$F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2}$	0.88	0.46	0.005	-0.40	0.005			0.29	0.10
5	$F_{ave} = \theta_0 P_{total}^{\theta_1} w_{eff}^{\theta_3}$	0.76	0.35	0.010			1.5	0.005	0.08	0.005
6	$F_{ave} = \theta_0 D_{exit}^{\theta_1} w_{eff}^{\theta_2}$	0.67			-0.30	0.010	1.1	0.060	2.2	0.120
7	$F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2} w_{eff}^{\theta_3}$	0.90	0.44	0.005	-0.37	0.005	0.34	0.335	0.29	0.015

While exit distance consistently shows a negative correlation (greater distance leads to a slower mean flow), the relative importance of effective stair width is not as clear with typically higher p-values. Also note that in the correlations that include effective width, the exponent for effective width varies widely from correlation to correlation. The range is from 0.35 to 1.96 while both exit distance and number of occupants have exponents with similar values. The R^2 does not increase nearly as much when adding in effective width.

One of the reasons that effective width does not explain more variation is that it is highly correlated with exit distance and number of occupants. This is not surprising since, as mentioned in Section 2.3, code requirements for stair design are based both on the number occupants on each floor of the building and to a lesser extent, the number of floors in the building. Together, exit distance and number of occupants explain almost 50 % of variation in effective width. For this reason it is not possible to say that effective width does not have an impact on the mean flow.

The following simple correlation based on Model 4 with rational roots was found as the best fit to the data with an R^2 of 0.88:

$$F_{ave} = 0.42\left(\frac{P_{total}}{D_{exit}}\right)^{1/3} \tag{16}$$

where F_{ave} is the mean flow out the exit door in persons/s, P_{total} is the total number of people using the stairs, and D_{exit} is the maximum distance travelled by people using the stairs. This correlation was found to work well for the middle 90 % of those exiting the stairs.

As an example, consider a building where the stair configuration (i.e., the distance traveled to leave the floor or exit distance), and the population per floor are exactly the same for all floors. Defining the population per floor as P_f and the distance traveled as D_f, then the total population and exit distance are $N*P_f$ and $N*D_f$, respectively, where N is the number of floors. Substituting into Eq (16), the flow at the exit is equal to a constant times the ratio of the P_f and D_f. The exit time for the middle 90 % is then equal to the total population over the mean flow or

$$T_N = \frac{NP_f}{F_{ave}} = \frac{NP_f}{0.42\left(P_f/D_f\right)^{1/3}} = 2.4NP_f^{2/3}D_f^{1/3} \tag{17}$$

where T_N is the total time it takes the middle 90 % to exit. So, the total exit time for middle 90 % is linear to the number of floors provided all the floors are identical.

5.4 Point Process Modeling of Egress Timing

In section 5.3, important variables that impact occupant flow in stairs were considered. In this section, the same variables are examined to better understand their impact on the timing of evacuation for each occupant and the interactions between occupants as they evacuate the building. Many models that simulate egress as a flow (i.e., hydraulic models) exist in the literature. They range from simple empirical data models to more elaborate fire dynamic simulators that use methods of mechanics, fluid dynamics and stochastic differential equations to describe the motion in human egress, see, for example, Section 2.4.

In this report, a new approach is taken. Flow is modeled as a point process[21]. Specifically, flow through the entrance or exit door of a stair is modeled as a point process [77, 78]. This approach uses only assumptions that are natural for the data. In general, exit times for individuals in a given building evacuation are not independent of each other due to human to human interaction within stairs and within exit corridors. Thus, a point process model that captures these dependences is required. This new approach, though probabilistic, agrees with results used in common practice flow models (for example, see section 5.4.2).

The dynamics of any flow are driven by the interaction of its fluid particles. A point process model provides a different type of data set than that provided by most flow models. Rather than an unstructured list of occupant exit points, it provides a curve of time correlated exit points, i.e. intensity functions and their compensators (compensators are cumulative intensity functions). Both the intensity function and compensator uniquely identify a point process[22]. To understand the underlying structure of these functions, statistical functional data analysis (fda) can be applied.

With fda, classical statistical techniques, where data points are individual real numbers are extended to data points that are functions or curves. Many of the same statistical techniques that hold for point data sets hold for functional data sets. Usually, these functions are assumed to lie in $L_2[0,T]$, the space of square integral functions on a finite set $[0,T]$. Means, variances, clustering techniques and regression are performed on sets of functions. Because an intensity function, λ and compensator function, Λ, is associated with each stairwell, fda can be readily applied to the set of all stairs, $\lambda_i(t) = \{\lambda_i(t,\hat{\theta}), i = 1,\ldots,n\}$ and $\Lambda_i(t) = \{\Lambda_i(t,\hat{\theta}), i = 1,\ldots,n\}$. For example, regression methods of functional data analysis can be used to model stair intensities as a function of the parameters that describe stair geometries. In addition, since these functions capture the interactions between data points, they can also be used to better understand the

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[21] In statistics and probability theory, a point process on a real line (such as a time line) is a set of isolated data points that can be described by the correlated intervals between the points. They have been extensively studied in statistics and probability theory.

[22] In this report, the Hawkes point process model is used which predicts the intensity as a function of the distribution of flow over time for each dependent variable of interest. The three parameters in the Hawkes model, μ, α, and β provide a quantitative measure of the background intensity, the likelihood of formation of clusters of occupants, and the size of these clusters during the evacuation, respectively. The compensator is a piecewise integration of the intensity function and can be roughly thought of as a cumulative probability function. Appendix E includes details of point processes and the Hawkes model.

interactions between occupants and thus hold promise to improve egress modeling by incorporating both the effects of the physical stair geometry and of the interactions between evacuees during stair evacuation.

The Hawkes point process model [79-81] used in this report captures occupant to occupant interaction during evacuation that does not appear in previous models. Details of the use of the Hawkes point process model in the context of evacuation timing is included in Appendix E.

Associated with each stair are three flow point processes, pre-observation time, travel time and total exit time. All three processes are modeled as Hawkes processes to determine maximum likelihood estimates. The intensity function (see Appendix E for details) for the exit times $t_1 < t_2 < \cdots < t_n$ modeled as a Hawkes point process is given by

$$\log L(t_1,\ldots,t_n \mid \mu,\alpha,\beta) = -\mu t_n + \sum_{i=1}^{n} \frac{\alpha}{\beta}(e^{-\beta(t_n-t_i)} - 1) + \sum_{i=1}^{n} \log(\mu + \alpha A_i) \tag{18}$$

where $A_i = \sum_{t_j<t_i} e^{-\beta(t_i-t_j)}$ for $i \geq 2$ and A_i=0. The three parameters, μ, α, and β can be taken as indicators of the average baseline intensity of the occupant flow (roughly an indicator of the average flow in the stair), the average intensity of interactions between occupants in the flow (roughly an indicator of how occupant interactions impact the average flow), and how quickly the interactions dissipates (or how quickly the intensity returns to the baseline intensity following interactions), respectively. For stair evacuation, these interactions include clustering of occupants into groups and its impact on evacuation timing. Thus, while μ is roughly analogous to the flow discussed in the previous section, both α and β provide additional information of the nature of the flow. Determining the parameters that influence μ, α, and β can provide additional understanding of the importance of the various measured variables in the evacuations.

5.4.1 Important Parameters Influencing Occupant Egress

Maximum likelihood estimates for the three parameters were found using the Nelder-Mead nonlinear optimization algorithm. All computations used the global routine "NMaximize" with constraints $\mu > 0,\ \alpha > 0,$ and $\beta > 0$ in Mathematica. When ties arose among the t_i, they were broken by adding a small amount of noise, ε, where ε is a uniform random variable on $[-\sigma,\sigma]$, $\sigma = 0.25$. This is within the uncertainty of the measurements. Table 12 and Table 13 contain the results. In addition to estimates for μ, α, β, and the average intensity, the table also shows the branching ratio, α/β.

Table 12. Maximum likelihood estimates for pre-observation times for each stairwell.

Stair No.	Number of Occupants	μ (background)	α (magnitude)	β (time decay)	Average intensity	Branching ratio
1A	129	0.0289	0.0997	0.1080	0.3423	0.9229
1B	143	0.0848	0.1270	0.1593	0.3816	0.7971
2South	126	0.0240	0.1261	0.1344	0.3410	0.9377
3East	119	0.0471	0.1171	0.1274	0.4646	0.9186
3West	100	0.0660	0.0984	0.1169	0.3839	0.8414
4A	244	0.0134	0.1463	0.1560	0.2024	0.9377
4B	354	0.0121	0.1209	0.1256	0.2973	0.9624
5A	432	0.0190	0.1417	0.1468	0.5039	0.9648
5B	361	0.0093	0.1180	0.1212	0.3151	0.9740
6-5	98	0.0291	0.0984	0.1102	0.2441	0.8924
6-5a	148	0.1197	0.0527	0.0744	0.3744	0.7086
6-6	114	0.0010	0.0857	0.0869	0.0415	0.9858
6-6a	217	0.0156	0.0933	0.0973	0.2939	0.9593
7-1	261	0.0180	0.0832	0.0884	0.2901	0.9415
7-3	293	0.0177	0.0951	0.1009	0.2931	0.9428
7-7	343	0.0120	0.0670	0.0701	0.2542	0.9567
7-12	195	0.0337	0.1045	0.1161	0.3226	0.9004
8N	665	0.0252	0.1153	0.1207	0.5464	0.9553
8S	525	0.0092	0.1070	0.1092	0.4093	0.9802
9A	70	0.0076	0.0668	0.0923	0.0265	0.7244
9B	56	0.0022	0.0316	0.0355	0.0176	0.8924
10-2	42	0.0136	0.3832	4.6493	0.0148	0.0824
11-2	135	0.0530	0.1545	0.1962	0.2333	0.7877
11-3	89	0.0037	0.0989	0.1028	0.0642	0.9623
12A	64	0.2238	0.1265	0.1984	0.5865	0.6376
12B	12	0.0777	0.2691	0.5626	0.1384	0.4783
13-1	32	0.0158	0.0541	0.0742	0.0539	0.7286
13-2	28	0.0143	0.0364	0.0525	0.0442	0.6943
14-1	175	0.0372	0.0647	0.0766	0.2228	0.8441
14-2	130	0.0185	0.1273	0.1453	0.1399	0.8766

Table 13. Maximum likelihood estimates for stair travel times for each stairwell.

Stair No.	Number of Occupants	μ (background)	α (magnitude)	β (time decay)	Average intensity	Branching ratio
1A	129	0.2841	0.4468	0.5625	1.3368	0.7942
1B	143	0.1439	0.4375	0.5629	0.5992	0.7773
2South	126	0.1129	0.2771	0.3474	0.5395	0.7977
3East	119	0.1666	0.2862	0.3841	0.6085	0.7451
3West	100	0.1155	0.5688	0.7413	0.4645	0.7674
4A	244	0.1832	0.5033	0.7599	0.5381	0.6623
4B	354	0.1913	0.6688	0.9351	0.6516	0.7152
5A	432	0.1679	0.3853	0.4769	0.8500	0.8080
5B	361	0.1456	0.5747	0.7296	0.6784	0.7877
6-5	98	0.0295	0.3387	0.4583	0.1099	0.7391
6-5a	148	0.0486	0.4241	0.5328	0.2313	0.7960
6-6	114	0.0319	0.2489	0.3416	0.1132	0.7287
6-6a	217	0.0391	0.4043	0.5025	0.1962	0.8046
7-1	261	0.1613	0.2910	0.4103	0.5490	0.7093
7-3	293	0.3893	0.4175	0.8256	0.7847	0.5057
7-7	343	0.2239	0.4045	0.6941	0.5295	0.5828
7-12	195	0.2550	0.3624	0.6038	0.6325	0.6002
8N	665	0.2604	0.2194	0.3217	0.8147	0.6820
8S	525	0.1154	0.2746	0.3505	0.5289	0.7835
9A	70	0.0320	0.0307	0.0426	0.1087	0.7201
9B	56	0.0057	0.0448	0.0491	0.0543	0.9118
10-2	42	0.0586	0.0336	0.0595	0.1300	0.5653
11-2	135	0.0732	0.4002	0.5460	0.2646	0.7329
11-3	89	0.0921	0.3746	0.8647	0.1603	0.4332
12A	64	0.3150	0.6232	1.0389	0.7512	0.5998
12B	12	0.0503	0.1772	0.2256	0.1444	0.7852
13-1	32	0.0497	0.1495	0.4944	0.0703	0.3025
13-2	28	0.0224	0.1447	0.1814	0.0972	0.7976
14-1	175	0.0623	0.5394	0.8248	0.1733	0.6540
14-2	130	0.0883	0.3224	0.5319	0.2173	0.6062

Like the previous section, both linear multiple regression and Bayesian inference can be used to determine the relative importance of quantities measured during the evacuations as related to the average intensity estimated by point process modeling by the same parameter estimation methods (see Appendix E for details). To determine the predictive influence of each engineering variable on flow, the following linear model is assumed

$$m_j = \theta_0 + \theta_1 x_{1,j} + \theta_2 x_{2,j} + \cdots + \theta_p x_{p,j} + error \tag{19}$$

where the dependent data variables are ($m_1, m_2, \ldots, m_{31}$), the independent variables, $x_{1,j}, x_{2,j}, \ldots, x_{p,j}$ are the engineering variables of interest, e.g., stair width, tread depth, tread height, and other variables. Linear least squares and Bayesian inference were used to estimate the parameters $\theta_0, \theta_1, \ldots, \theta_p$ and hypothesis tests are used to determine whether an engineering variable contributes significantly in explaining variability in the dependent variable.

The first results are for the average intensities of pre-observation time, travel time and total exit time. Six parameters and the constant were found to be significant for at least one of the three average intensities. They are the number of occupants, P_{total}, exit distance, D_{exit}, if the building is residential or non-residential, B_{type}, the stair riser dimension, s_{riser}, the stair tread dimension, s_{tread}, a flag indicating if a stair travel device was used at any time during evacuation, F_{chair}, and finally a constant, c.

Table 14 shows the R^2 for each of the fits, the estimate of the coefficient for each variable and the p values for the coefficients which tested as significant using LLS. If a building parameter does not have a value for a particular average intensity it means that parameter did not test as significant. Table 14 also shows the deviance information criterion, DIC, the estimate of the coefficients, and the probability that the actual value is a different sign from the median for the three models using Bayesian inference to determine the coefficients.

For all three average intensities P_{total}, D_{exit}, and B_{type} are all significant. For the average intensity of travel time, two additional building parameters are significant: s_{riser} and s_{tread}.

The signs for the three building parameters that are common, P_{total}, D_{exit}, and B_{type}, are the same across the different average intensities. The coefficients for the building parameters for pre-observation time and exit time had the same order of magnitude, but differed from the order of magnitude for the number of occupants and exit distance for the travel time. Finally, there is a clear logic to the fact that the step dimensions do not impact the average intensities for pre-observation time and exit time but do for travel time. In the pre-observation period, the occupants were not interacting with the stairs. While the occupants do interact with the stairs on their way to the exit door, the fraction of the total exit time any occupant spends on the stairs varied significantly, so the impact of the stairs on the total exit time varied as well. However, for the travel time in the stairs, the dimensions of the stairs can have a significant impact on the average intensity.

Table 14. Building parameters that correlate with average intensity using LLS and Bayesian Inference

Linear Least Squares						
Building parameters, θ_i	Pre-observation Time		Travel Time		Total Exit Time	
	Coefficient	p value	Coefficient	p value	Coefficient	p value
R^2	0.61		0.81		0.84	
P_{total}	0.040	0.015	0.12	0.005	0.061	0.005
D_{exit}	-0.036	0.015	-0.13	0.005	-0.037	0.005
B_{type}	-0.23	0.005	-0.22	0.055	-0.15	0.005
s_{riser}			9.35	0.030		
s_{tread}			4.88	0.055	1.30	0.055
F_{chair}					-0.090	0.025
θ_0	0.29	0.020	-2.53	0.080	-0.22	0.315

Bayesian Inference						
Building parameters, θ_i	Pre-observation Time		Travel Time		Total Exit Time	
	Coefficient	95 % CI	Coefficient	95 % CI	Coefficient	95 % CI
DIC	-43.8		-24.1		-72.6	
P_{total}	0.042	[0.01, 0.07]	0.12	[0.08, 0.17]	0.061	[0.04, 0.08]
D_{exit}	-0.036	[-0.06. -0.01]	-0.12	[-0.17, -09]	-0.036	[-0.05,-0.02]
B_{type}	-0.22	[-0.36, -0.10]	-0.21	[-0.42, 0.02]	-0.14	[-0.23, -0.05]
s_{riser}			9.7	[2.18, 17.69]		
s_{tread}			5.1	[0.43, 9.66]	1.34	[0.00, 2.71]
F_{chair}					-0.11	[-0.18, -0.04]
θ_0	0.28	[0.06, 0.51]	-2.7	[-5.28, 0.10]	-0.22	[-0.66, 0.21]

P_{total} is the total population of evacuees using the stair, D_{exit} is the maximum distance travelled by an evacuee in the stair, B_{type} is the building type (office or residential occupancy), s_{riser} is the tread riser height, s_{tread} is the tread depth, F_{chair} indicates the presence or absence of a stair travel device in the stair, and θ_0 is a constant in the linear model from eq. (19).

Stair Width: In terms of the capacity requirements, both the International Building Code and the Life Safety Code directly correlate incremental increases in stair width with increased capacity. More specifically, stair capacity factors (i.e., 5 mm (0.2 in) of required stair width per person on an occupied floor in the building) are used to calculate a required stair width (with a minimum stair width specified as 1118 mm (44 in) wide in both the IBC and the LSC[23]). The LSC further requires an increase in the minimum stair width to 1422 mm (56 in) for buildings serving equal to or greater than 2000 people).

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[23] The minimum requirement exists for stairways serving greater than 50 people, and less than 2000 people in the LSC.

Before prescribing the use of stair capacity factors, the IBC and NFPA codes relied on the concept of exit lanes. The exit lane concept argues that benefits in stair efficiency (e.g., flow and speed on stairs) are seen only after step-wise increases in lanes of stair width, rather than incremental increases in width. Lanes of stair width are distances equivalent to the width of a person, shoulder to shoulder, or a mean of 559 mm (22 in) in width.

Current debates in the code communities have questioned the appropriateness of the prescriptive minimum stair widths required by the IBC and NFPA codes – inquiring if 1118 mm (44 in) of stair width is enough? Also questioned is the appropriateness of the use of capacity factors versus exit lane capacity to calculate required stair widths. Therefore, the evaluation of the performance of the critical threshold widths, as well as various other widths, was important for assessing the efficacy of common building code requirements for stairway construction.

Using point process modeling, the influence of effective width on stair efficiency was tested, measured here as increased stair flow. Stair flow was measured at the bottom of the stairs, located at the exit door from the stair. Since there was no queuing witnessed at the stair doors in each stairway, effective stair width was used in the analysis of stair flow efficiency. The results of the Hawkes model showed that incremental increases in stair width did not show a significant increase in average stair flow across the building sample in this study.

On first glance, it seems that these results simply state that increasing the stair width does not increase the overall stair flow. However, the results show that that is not necessarily the case. In fact, most of the models in Table 11 and Table 14 show a positive (power law) correlation between mean flow and effective width (R^2=0.39) and a positive (power law) correlation between mean flow and the dependent variables of total population in the stair and effective width of the stair (R^2=0.59). These results are contradicted by the results displayed in Table 11 that show a strong correlation between mean flow and the dependent variables total population of the stair and exit distance (R^2=0.78), with effective width improving the correlation less than 2 %.

Some of this may be simply because typical building design calls for increased stair capacity (typically by increased stair width) as floor population in the building increases. In addition, effective width is well correlated with two other independent variables: travel distance and total population in the stairs. Thus, while the point process modeling results of this research do not show a significant relationship between stair effective width and mean flow, this study is not able to definitely state that incremental increases in stair width is inconsequential to mean stair flow.

Another possible explanation for the contradiction in findings (on the effect of stair effective width) is the lack of variance in effective width among NIST-observed building samples. All of the buildings observed in this study are code-compliant buildings with effective stair widths ranging from 756 mm (29.75 in) to 1232 mm (48.5 in), with the majority (62 %) of stairs falling within the narrow range of 729 mm (28.7 in) to 813 mm (32 in). Additional observation and analysis of tall buildings in the United States and experimentation in a laboratory setting of evacuations using a wider range of stair widths are needed to quantify the benefits (or lack thereof) of incremental stair widths versus the exit lane theories[24].

Riser Height: In the correlations, it should be noted that if the building occupancy type, B_{type}, is not included then the stair riser height, s_{riser}, would also test as significant. The reason can be seen in Figure 16. There are several buildings in both type 2 residential and type 1 non-residential with stair riser heights, s_{riser}, of 0.16 m but only type 2 buildings have lower risers and only type 1 buildings have taller risers. In effect the riser height can act as a flag for the type of building. Thus, while all the buildings were consistent with building code requirements allowable differences in stair riser height happened to also correlate with building occupancy type.

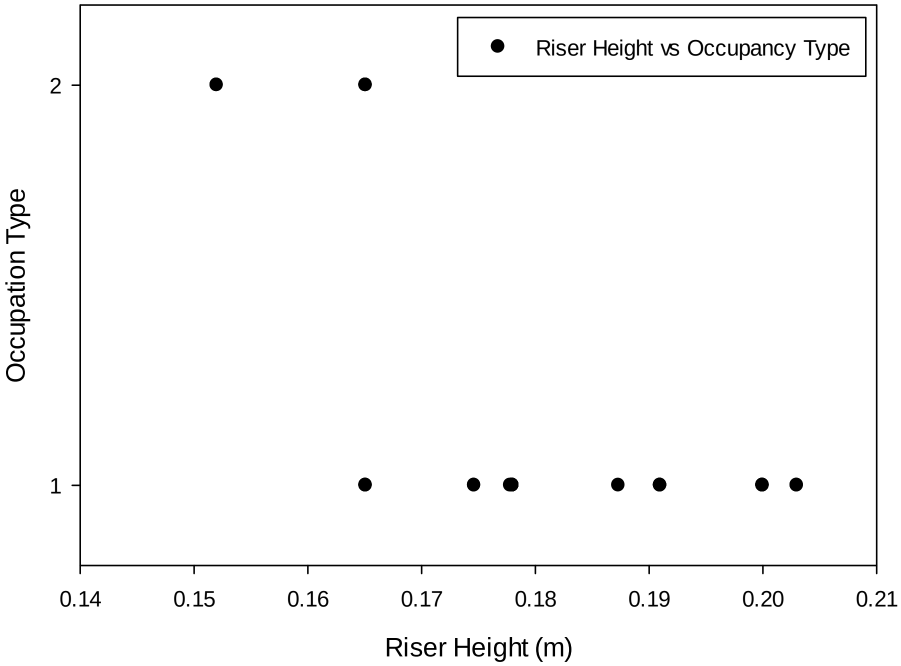

Figure 16. Riser height vs. occupant type flag (1 - non-residential, 2 - residential)

In addition to the average intensities, it is of interest to examine the relation of the three parameters, μ, α, and β that make up the intensity function since they provide information on the interactions between occupants during evacuation. Table 15 presents information for μ, similar to that presented for the average intensity in Table 14.

None of the building parameters tested passed the significance test correlating μ with exit times. While P_{total} and B_{type} tested as significant for the pre-observation time μ, they only explain 21 % of the variation. Interestingly, the sign for number of occupants is opposite of what it is in the

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[24] Consideration of exit lanes should also account for the number of doors (and door width) placed at the bottom of the stairs.

correlation of average intensity. For travel time, the sign of the coefficient for D_{exit} is the same both for the μ as it is for the average intensity, however, P_{total} is not significant. For both pre-observation time and travel time, μ are lower for residences than for non-residences. Since μ is analogous to the background or underlying mean flow, this fits with the observations made in section 5.2.

Table 15. Building parameters that correlate with μ determined by LLS and Bayesian inference

Linear Least Squares

Building parameters, θ_i	Pre-observation Time		Travel Time		Total Exit Time	
	Coefficient	p value	Coefficient	p value	Coefficient	p value
R^2	0.26				0.0	
P_{total}, θ_1	-0.015	0.020				
D_{exit}, θ_2			-0.049	0.005		
B_{type}, θ_3	-0.064	0.015	-0.18	0.005		
θ_0	0.13	0.005	0.45	0.005		

Bayesian Inference

Building parameters, θ_i	Pre-observation Time		Travel Time		Total Exit Time	
	Coefficient	95 % CI	Coefficient	95 % CI	Coefficient	95 % CI
DIC	-101.9		-69.3		-129.4	
P_{total}, θ_1	-0.014	[-0.03, -0.001]			0.002	[-0.005,0.01]
D_{exit}, θ_2			-0.037	[-0.06,-0.02]	-0.003	[-0.01, 0.003]
B_{type}, θ_3	-0.06	[-0.11,-0.01]	-0.15	[-0.22, -0.8]	-0.018	[-0.05,0.01]
θ_0	0.12	[0.05,0.19]	0.36	[0.25, 0.47]	0.033	[-0.02, 0.01]

P_{total} is the total population of evacuees using the stair, D_{exit} is the maximum distance travelled by an evacuee in the stair, B_{type} is the building type (office or residential occupancy), and θ_0 is a constant in the linear model from eq. (19).

5.4.2 *Clustering of Occupants During Egress*

Occupant exit times are not uniformly distributed. The plots in Figure E-1 in Appendix E illustrate this. There were short periods of very intense flow and periods of very low intensity flow due to occupant interactions. Thus, exit times are irregular, cluster and pose a challenge for modeling exit flow. In order to better understand the dynamics of occupant egress, it is necessary to formulate causes of clustering and then to incorporate them into an explanatory model. The phenomenon of clustering, also called grouping or platooning is not new. Clustering has been observed in high rise building evacuations and is discussed in the literature, but without technical analysis, see Pauls [57], Kagawa [36] and Proulx [3]. Hoskins [56] observed that the movement speed of those following the first person in a cluster was correlated to the speed of the leading person for selected stairs from this data set. Finally, Baker studied platooning in high rise buildings and his thesis contains additional references [82].

One way to better understand clustering in occupant egress is to divide decisions made by occupants during an evacuation into those driven by internal mechanisms, i.e. arising from endogenous events and those decisions arising from exogenous events. Exogenous events are those driven by training, the urgency to exit the building quickly in face of an emergency and similar mechanisms. Endogenous events are driven by things like human to human interaction, etc. The Hawkes model allows one to measure the level of endogeneity in occupant egress, because the Hawkes intensity is separated into background intensity and an intensity driven by internal events. The background intensity parameter μ reflects the Poisson nature of the traffic, with the duration between events occurring independently and randomly with rate μ. When the events bunch together, they are no longer Poisson and this reflects the internal mechanisms interfering with descent.

An occupant with exit time t_i is either a "mother" or a "daughter" event of another point in the process. The parameter μ, the background intensity determines the rate mother events occur, which may or may not trigger second order events (daughter events), which can trigger third order events, and so. That is, a mother event occurring at rate μ can, through successive generations, create a cluster of events. These successive generations represent endogenously propelled events due to internal components and interaction within the stair. The branching ratio, n, is defined as the proportion mother events generate offspring events and is defined by the ratio

$$n = \frac{E[\lambda(t)] - \mu}{E[\lambda(t)]} \tag{20}$$

The intensity[25], $\lambda(t)$, by definition satisfies $\lambda(t) = \mu + \alpha \int_{-\infty}^{t} e^{-\beta(t-s)} dN(s)$, thus for moment stationary intensities

$$\begin{aligned} E\left[\lambda(t)\right] &= E\left[\mu + \alpha \int_{-\infty}^{t} e^{-\beta(t-s)} dN(s)\right] \\ &= \mu + \alpha \int_{-\infty}^{t} e^{-\beta(t-s)} dE\left[N(s)\right] \\ &= \mu + \alpha \int_{-\infty}^{t} e^{-\beta(t-s)} E\left[\lambda(s)\right] ds \\ &= \mu + E\left[\lambda(t)\right] \int_{-\infty}^{t} e^{-\beta(t-s)} ds \\ &= \mu + E\left[\lambda(t)\right] \int_{0}^{\infty} \alpha e^{-\beta(s)} ds \end{aligned} \tag{21}$$

Solving gives an expression for the branching ratio

$$n = \frac{E[\lambda(t)] - \mu}{E[\lambda(t)]} = \int_{0}^{\infty} \alpha e^{-\beta(s)} ds = \frac{\alpha}{\beta} \tag{22}$$

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[25] The three parameters in the Hawkes model, μ, α, and β provide a quantitative measure of the background intensity, the likelihood of formation of clusters of occupants, and the size of these clusters during the evacuation, respectively.

For general point processes, α/β is taken as the branching ratio even though the process may not be stationary. The branching ratio provides a simple characterization of traffic within a stair, in particular its susceptibility to internal shocks to the traffic. On average, for $n < 1$, $1 - n$ proportion of occupants arrive at the exit door without being affected by internal mechanisms. For fixed μ, as the branching ratio increases, the intensity of the traffic decreases. From eq. (18),

$$E\left[\lambda(t)\middle|\mathcal{H}_t\right] = \frac{\mu}{1-\frac{\alpha}{\beta}} \qquad n = \frac{\alpha}{\beta} < 1 \tag{23}$$

Figure 17 shows the relationship for the data from this study. The average, $\frac{1}{t}\int_0^t \lambda(s)ds$, can be substituted for the left-hand side of eq. (23) and the plot below illustrates that this substitution works well.

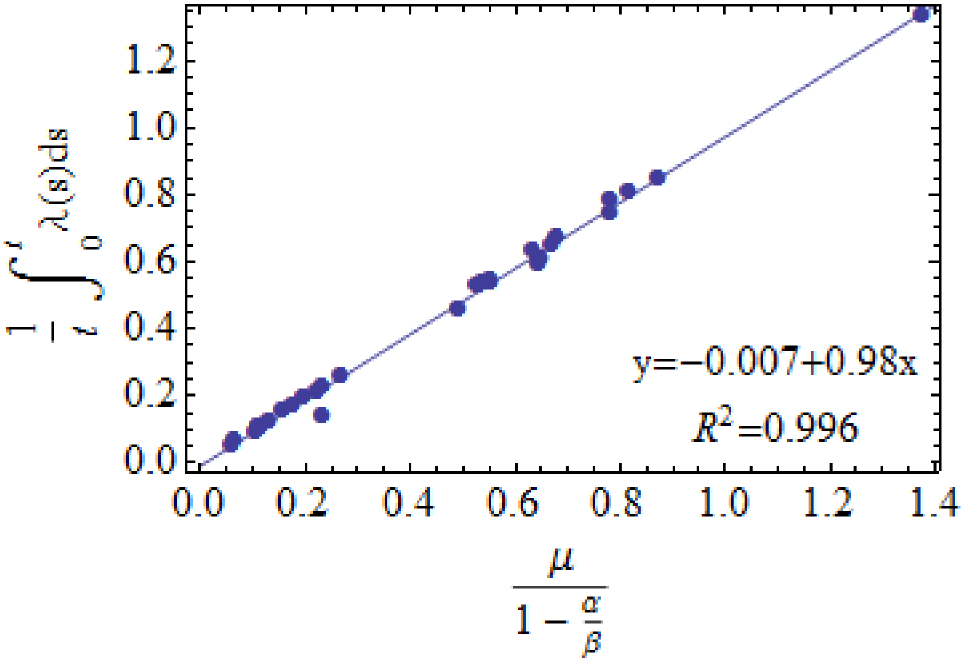

Figure 17. Fundamental relationship between branching ratio and average intensity with data from 31 stair evacuation travel times.

Fruin [37] and Paul's [57] research on flow rates is used and referenced by fire safety engineers today. One of their results relates occupant density D in persons/m^2 to flow rate. For F_s, the flow per unit stair width, they found the following relation

$$F_s = kD - akD^2 \tag{24}$$

where a and k are constants. One obvious diagnostic check for the point process approach is to determine if the average intensity satisfies this relationship with D. In Figure 18, the mean intensity, $\frac{1}{t}\int_0^t \lambda(s)ds$ is plotted against stair density. Here, stair density is defined as the average number of persons per floor divided by (the linear length of the stair between floors times the effective width of the stair). The model fit yields an R^2 of 0.74.

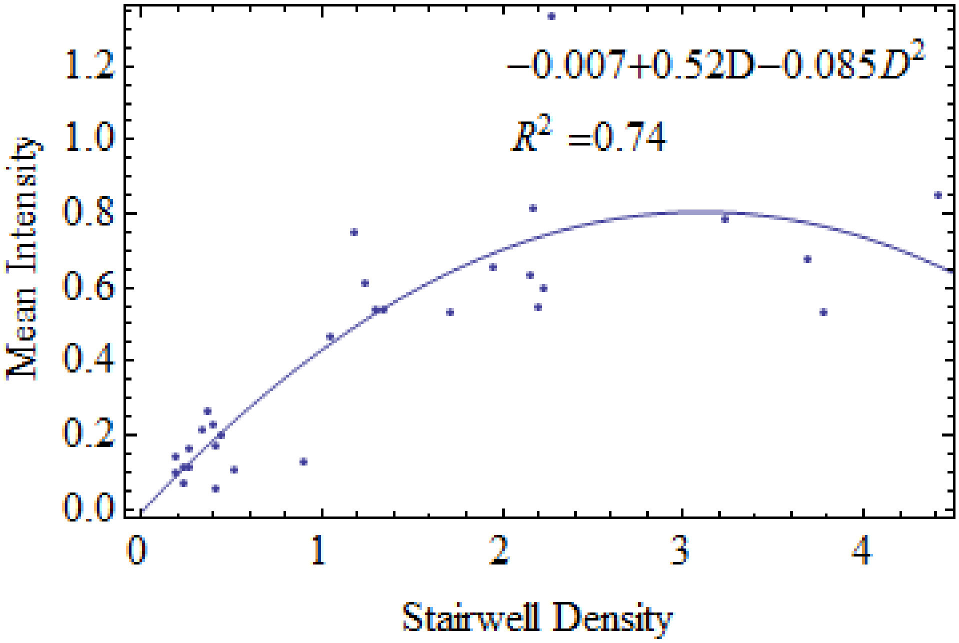

Figure 18. Point process intensity compared to stair density. Note quadratic form consistent with current relationship between flow and density.

To understand the impact of building design parameters on the branching ratio, those parameters that impact α are first considered. Table 16 shows the building parameters that correlate with α. For both travel time and exit time, the LLS and Bayesian methods provide very similar answers. LLS values are all within the credible confidence interval for the median of the Bayesian inference.

For pre-observation time, the 95 % CI in the Bayesian results include 0 and values of the coefficients are fairly close to 0 relative to the range. P_{total} is not 0.00 but rounds to 0.00 to the nearest hundredth. The interpretation of these differences is not clear. While these variables pass the significance test using LLS, Bayesian inference seems to indicate that there is little difference between the median values of the credible CI and 0. Since a model is being fit to pre-observation time, it is not unreasonable to wonder if stair parameters impact the pre-observation time. So, whereas there is a significant correlation using LLS, it seems that the better to choice is to assume that there is no correlation between stair parameters and pre-observation α.

Table 16. Building parameter correlations with α from LLS and Bayesian inference

Linear Least Squares						
Building parameters, θ_i	Pre-observation		Travel		Exit	
	Coefficient	p value	Coefficient	p value	Coefficient	p value
R^2	0.49		0.51		0.59	
B_{type}	-0.12	0.005	-0.32	0.005	-0.048	0.030
w_{eff}	0.09	0.090				
s_{tread}	-0.96	0.105				
Landing Door Location					0.016	0.025
D_{exit}					0.012	0.010
P_{total}	-0.13	0.020			-0.022	0.005
θ_0	0.29	0.020	0.40	0.005	0.13	0.005

Bayesian Inference						
Building parameters, θ_i	Pre-observation		Travel		Exit	
	Coefficient	95 % CI	Coefficient	95 % CI	Coefficient	95% CI
DIC	-101.9		-69.3		-129.4	
B_{type}	-0.019	[-0.11,0.08]	-0.32	[-0.48, -0.18]	-0.056	[-0.10.-0.01]
w_{eff}	0.048	[-0.21, 0.28]				
s_{tread}	0.16	[-1.4, 1.8]				
Landing Door Location					0.016	[0.001,0.03]
D_{exit}					0.013	[0.004, 0.02]
P_{total}	0.00	[-0.03, 0.01]			-0.021	[-0.03,-0.01]
θ_0	0.0045	[-0.43, 0.54]	0.39	[0.34, 0.45]	0.11	[0.03, 0.20]

P_{total} is the total population of evacuees using the stair, D_{exit} is the maximum distance travelled by an evacuee in the stair, s_{tread} is the tread depth, w_{eff} is the effective stair width, B_{type} is the building type (office or residential occupancy), and θ_0 is a constant in the linear model from eq. (19).

In terms of correlations with β, there is only one parameter that correlates: α. Figure 19 plots α and β for all three cases, except two outliers. They are in stair 2 in building 10 for both the pre-observation time and exit time. As noted before, this stair is somewhat unique in the number of people using stair travel devices. The figure is β versus α, so that the slope is the branching ratio. Correlations using both a power law and linear relationship were tested to see which provided the best correlation. For LLS the R^2 was 0.93 for a linear relationship and 0.86 for the power law. For Bayesian inference, the DIC is -299.5 for the linear relationship and -283.3 for the power law. So, the following parameters were obtained from both methods as shown in Table 17.

Table 17. The results of fitting α in terms of β. Extra significant figures added to demonstrate the closeness of the results.

Method	c	β
LLS	0.0291	0.6075
Bayesian inference	0.0293	0.6070

Both methods yield the result that approximately 61 % of people in the stair evacuations were interacting with each other.

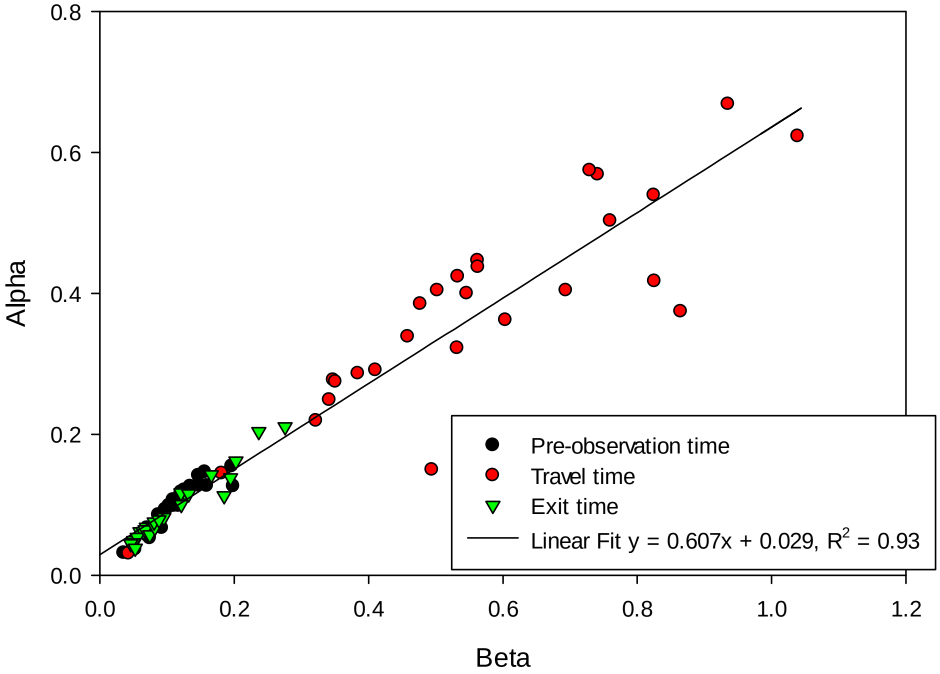

Figure 19. β vs. α and the linear fit.

The factors listed in Table 16 characterize the interaction between occupants. This means that occupants evacuating from residential buildings have less interaction than those in non-residential buildings in all three cases. For pre-observation time, there is more interaction as effective width increases. It should be noted that pre-observation time is not the same as pre-evacuation time. In fact, at peak densities on a stair landing, the crowding slows people as they enter the stairs. So the interaction between people entering the stairs and people already on the stairs reduces the interaction with other people entering the stairs. The wider effective width would allow people to enter the stair landing from both higher in the building and from the building floor together, possibly by reducing congestion on the landing.

For exit time, the door position for those entering the stairs near the same point that people are leaving the landing seems to increase the amount of interaction identified at the exit than having the door near where people enter the landing from upper floors. The longer the distance travelled down the stairs to the exit, the less the interaction.

The α for travel time does not correlate with any of the building parameters, with the exception of the type of occupancy. This is because the values for α in residential buildings were all lower values than the values calculated for non-residential buildings.

From the discussion above it is clear that the Hawkes model can be very useful in the understanding and characterizing of clustering of egress flows and that the analysis is in many ways consistent with earlier analyses of occupant flow as a function of stair density. There is still research to be done and most importantly there needs to be more data available.

5.5 Use of the Data for Detailed Analysis of Evacuee Movement

The data presented in this report can also be used to better characterize occupant movement. In this section, data from one of the buildings is analyzed in more detail to better characterize occupant movement on stair landings. First, the assumptions employed for the representation and modeling of evacuee behavior on stair landings are reviewed and discussed. Next, an exemplary application of the approach is presented for the study of human behavior on stair landings. Data from one of the six-story buildings (Building 12) are used.

5.5.1 Introduction

In Section 4 of this report, three main variables are employed for the analysis of occupant movement on stairs, namely 1) walking speeds 2) flows and 3) people densities. Hoskins and Milke [68] reviewed the current assumptions used to calculate speed and densities on stairs and have highlighted that data on evacuation movement on stairs may lack information on the assumptions employed, thus reducing the usability of the datasets.

These issues are reflected in the use of experimental data for the calibration of egress model inputs. Most of the egress models available are micro-simulation tools, i.e., individuals are treated as autonomous entities [83]. Nevertheless, datasets employed for the development and calibration of those models are based on average populations and hypotheses rather than an individual analysis of occupant behaviors. Occupants may be assumed to walk on a pre-determined travel path (generally the shortest path available or an assumed fixed route) and average deterministic assumptions are used to represent the actions of the individuals whose behaviors are instead probabilistic. The use of deterministic assumptions – intended as assumptions where no randomness is involved - to model occupant behaviors can decrease the accuracy of predictions compared to a probabilistic representation of people movement [84].

Evacuation data are generally not presented or used in a probabilistic manner. The closest that researchers come to a probabilistic description of people movement during evacuation is the use of distributions (e.g. a distribution of pre-observation times, a distribution of movement speeds, etc.) [2, 64]. The probabilistic approach to study people movement during evacuations in different environments has been rarely employed (e.g., the building egress model proposed by Fraser-Mitchell [85] or the train egress model by Capote et al. [86]). In addition, datasets - on which egress models are based - are not collected with the aim of providing a probabilistic representation of people movement.

To address this issue, a probabilistic approach has been proposed to present and use data on evacuation movement which is independent from the assumptions employed [87]. The approach relies on the reconstruction of the travel paths walked by the occupants and the recording of the time spent by the occupants during their journey. The probabilities associated with different travel paths, walking speeds and the space occupied by the evacuees during their movement can be then calculated.

The use of the probabilistic approach permits the analysis of the factors impacting evacuation on stairs because it increases the accuracy of data collected by reconstructing occupant movement. For instance, previous studies [48, 49] have shown that the understanding of occupant behaviors on stair landings is crucial since it may substantially affect the prediction of the evacuation process (and subsequent evacuation time calculations) given the occurrence of behaviors such as merging, deference/overtaking, etc.

Data from an evacuation drill performed in a six-story building (building 12) have been employed to demonstrate this approach. 215 individual trajectories on stair landings have been collected. The impact of two factors have been investigated, namely 1) the number of people on stair landings (crowding conditions) and 2) the type of interactions between the occupants. Interactions between occupants have been studied using a set of conditions based on a time-line which permitted the classification of different types of interactions, e.g., merging, deference/overtaking, etc.

The benefits of this approach are presented in relation to the current methods adopted in engineering practice to represent people movement on stairs. The present work also describes the advantages of the analysis of people movement data employing the new probabilistic approach from a modeling perspective. In fact, individual evacuation movement data can be aggregated using conditional probabilities, or employing a discretization of the space in a grid or a combination of both.

5.5.2 Tracking Travel Paths

The use of a probabilistic approach for the analysis of evacuation movement data relies on the tracking of individual occupant trajectories. Tracking individual trajectories allows the analyst to record travel path distance and area usage during evacuation (as shown by Nilsson and Peterson [88] - in this case, stair landings). An example of the new probabilistic approach to better represent stair evacuation data is presented in this section. The case study uses data from video recordings collected from Building 12.

The video analysis is focused on the study of the occupant travel paths, occupant usage of the landing area, and occupant walking speeds. A systematic approach has been used to track the travel paths from the video recordings. This method combines the use of a video analysis tool and measurements in CAD drawings. The observations focus on tracking the occupant's trajectories as well as the times when the occupants entered and left the space.

The analysis consisted of five steps:

Step 1: The video recordings are imported into a video analysis tool. This method is used to treat the uncertainties associated with the distortion of the recorded image in relation to the type of camera employed and the camera placement. Reference lines/grids are drawn on the floor on top of a physical grid made of squared tiles (they depend on the video set, in this example they are 30 cm on each side) that is visible in the video recordings. At the same time, a CAD tool is used to reconstruct the plane configuration of the landing (i.e., not distorted). An additional sub-grid (made of 10 cm wide squares) is overlaid onto it using the CAD tool in order to further increase the resolution of the measurements (See Figure 20).

Step 2: The location of the door into the landing is identified.

Step 3: Given the observed Fruin's level of service [37] on the landings and the availability of the physical grid made of tiles, it was possible to track the position of the feet of the occupants with a high level of accuracy directly from the video recordings. The trajectories of the occupants are therefore reconstructed following a point placed between the feet of each occupant in the grid (see point A Figure 21). In line with the dimensions of the cells of the sub-grid, the uncertainty of the position of the occupant is estimated to be always less than 20 cm.

Step 4: The trajectories are reconstructed in the plane configuration of the landings in the CAD tool.

Step 5: Given the trajectories of the individuals within the landing, it is possible to calculate the lengths of each travel path (starting from the point where occupants entered the landing until the point they left it).

Travel paths can be presented by a distribution of probabilities associated with different travel path lengths, termed here as Probable Travel Paths (PTP). Conditional probabilities can be used to understand the impact of specific conditions on occupant behaviors. An example is the analysis of the number of people on the landing when the occupant is approaching it. PTP lengths of the complete dataset of probable travel paths for Building 12 are presented (see Figure 22) considering the crowding conditions (condition 1) against their corresponding reference paths[26]. The comparison with reference paths (*h* in Figure 22 is used to indicate the observed path lengths as a ratio to a reference path, here taken to be the path down the middle of the stairs and around a landing, consistent with eq. (4) in section 3.3) is employed to evaluate the impact of the number of people in the landings other than the reference occupant on the length of the travel paths. Additional details and analysis can be found in reference [89].

The most probable travel paths in the complete sample are often shorter than the hypothetical paths (19 % of the sample are in the $-25\%<h<-15\%$ and $-15\%<h<-5\%$ intervals). Data show that occupants walking alone in the landing tend to walk shorter travel paths than the reference paths assumed [68], i.e., the observed most probable travel path length is from 35% to 25% shorter than the reference paths in the case of sinistral stairs and light density conditions.

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[26] For this analysis, the reference travel path is taken consistent with the calculations of travel distance and speed described in Section 2.2. See Figure 4 for an overview of the travel distance.

Physical (distorted) grid made of squared tiles

Artificial (distorted) overlapped grid

Artificial (distorted) grid reconstructed in CAD

Artificial (plane) grid and sub-grid reconstructed in CAD

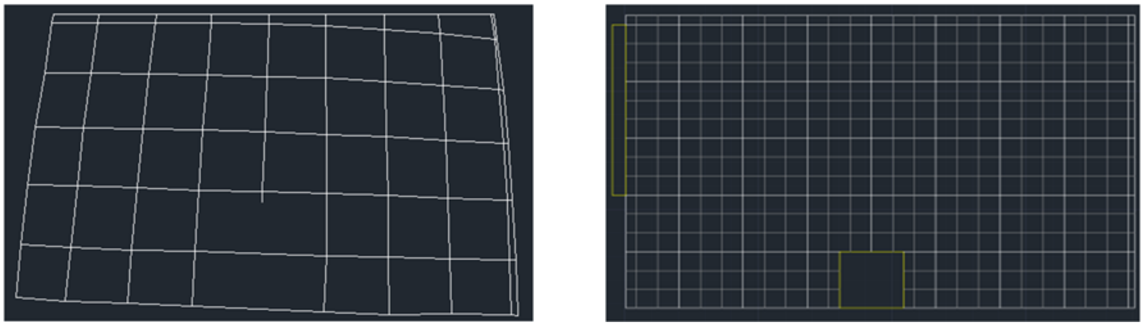


Figure 20. Example of the video analysis method for a stair landing.

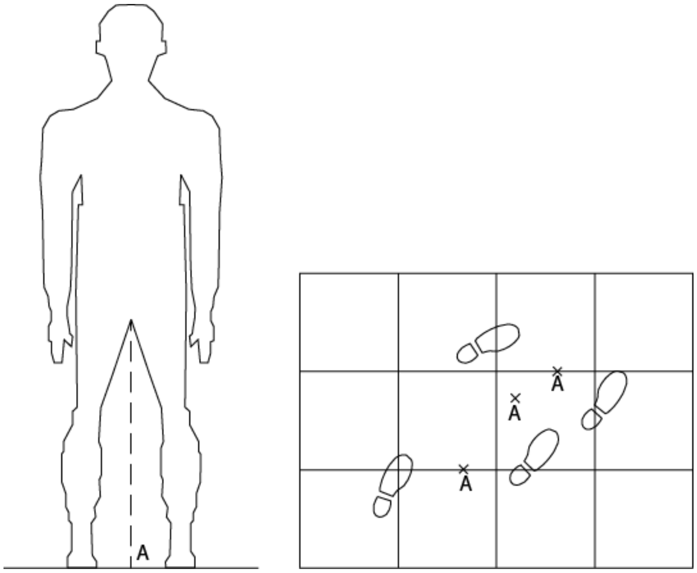


Figure 21. Schematic representation of the occupants. Point A represents the point used as reference for the reconstruction of the trajectories (the middle point between the feet).

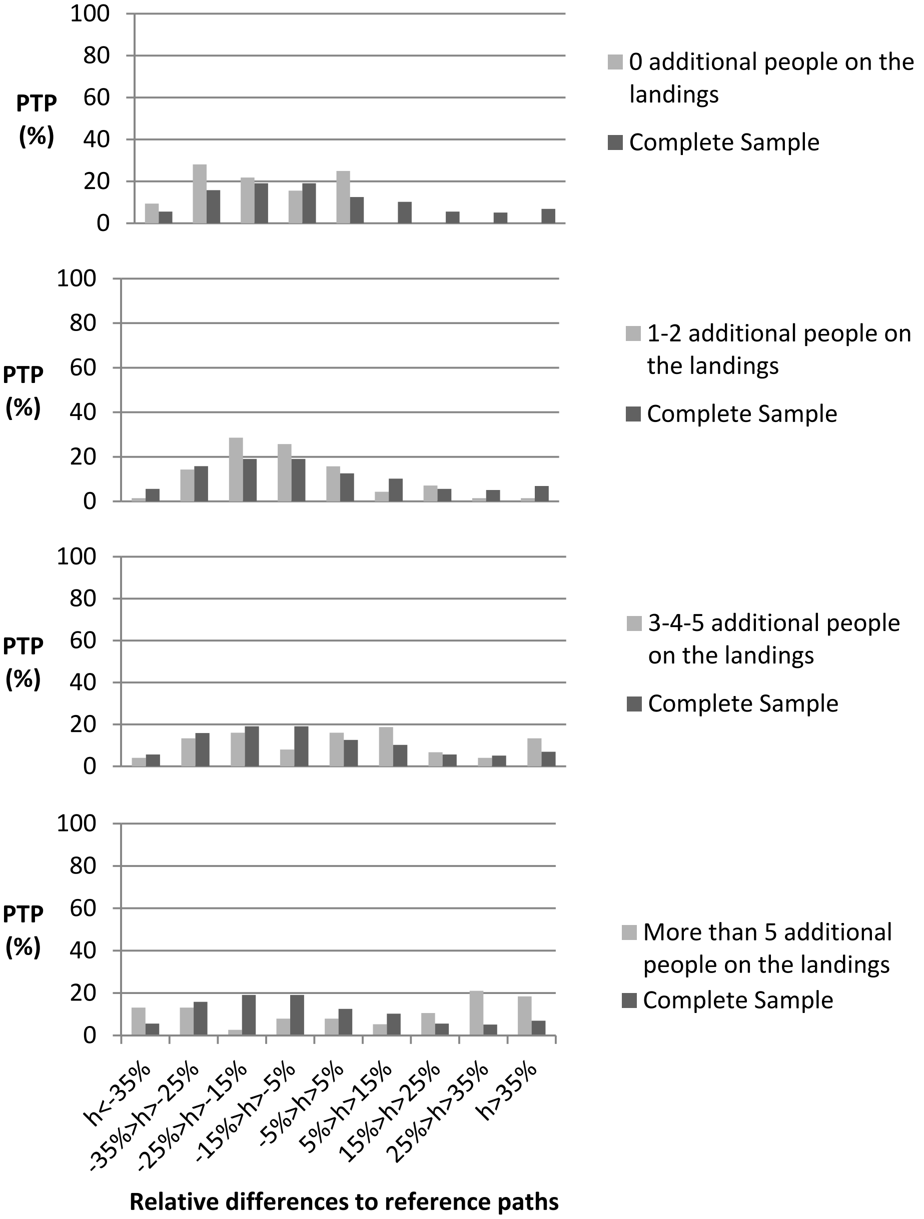


Figure 22. Complete sample of PTP lengths (black bars) against data presented compared to the additional number of people in the landings (grey bars). The x axis is the same in the four graphs and it represents the relative differences of the experimental path paths (h) and reference travel paths. The percentages indicate the intervals of relative differences to the reference paths.

5.5.3 Tracking occupant walking speeds

A systematic approach has been employed to calculate the walking speeds of the occupants in relation to their actual travel path.

The analysis has been performed in three steps:

Step 1. The actual travel path length of each individual is used as reference for the calculation of the walking speeds.

Step 2. The time and position where they enter (either from the door or the stair) and leave the landing is recorded using the video analysis tool.

Step 3. The individual speeds are calculated dividing the actual travel path of each occupant for the corresponding individual time spent in the landing.

The probabilities associated with different walking speeds, the Probable Walking Speeds (PWS), can be calculated. The probabilities are obtained in relation to different conditions such as congestion levels, merging flows, etc. The study of PWS provides additional understanding on the behaviors of the occupants (if compares with the study of PTPs only) since it takes into consideration both the spatial and the temporal information.

Figure 23 presents data on probable walking speeds in relation to condition 1, i.e. the number of people in the landings other than the reference occupant. The most probable walking speeds are respectively in the interval 0.75 m/s – 1 m/s in the cases of 0 or 1-2 additional people in the landings (respectively 40.6 % and 55.7 %). Most probable walking speeds are lower (in the interval 0.5 m/s – 0.75 m/s) in the case of 3-4-5 and more than 5 additional people in the landings (respectively 52.0 % and 50.0 %). Data show also that probable walking speeds tend to decrease with the increase of the number of people in the landing. Additional details and analysis can be found in reference [89].

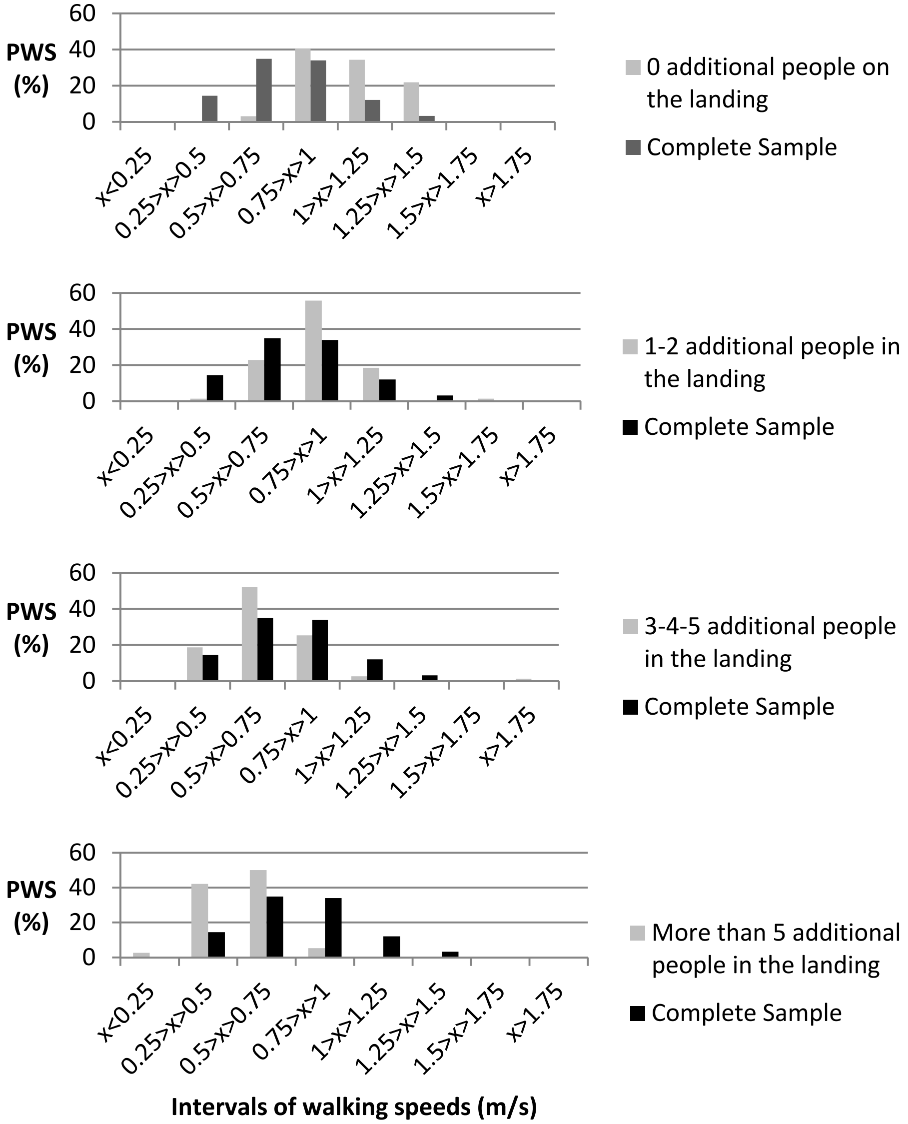


Figure 23. PWS (expressed in %) in relation to the number of occupants in the landing (condition 1). Walking speeds are indicated within the intervals where the speeds (x in the figure axis) fall.

5.5.4 Tracking occupant usage of landing areas

Although travel paths provide useful information on occupant behaviors on stair landing areas, current engineering calculations assume hypothetical area usage to calculate people densities [68]. In this context, the tracking of occupant travel paths may be employed to evaluate current assumptions and obtain a more accurate representation of occupant usage of landing areas. This permits the performance of calculations based on the experimental travel paths rather than hypothetical assumptions. A systematic approach has been employed to monitor the sub-areas of the landings occupied by the evacuees over the entire building evacuation.

The analysis has been performed in four steps:

Step 1. The trajectories described the previous section are used as a foundation for the development of area usage as well as the grids drawn in CAD.

Step 2. The areas occupied by the occupants are produced by assuming an average body size of the occupants equal to an ellipse with a diameter of 0.5 m [90, 91] (see Figure 24). This assumption is made since travel paths refer to the center line of the body while the body size is representative of the space occupied by a person (which includes shoulders). For instance, different body widths may be employed for different population types (e.g., children, adults). The area occupied by the evacuees is therefore represented as a moving ellipse and it is simplified by a perpendicular bar moving in the space (see Figure 25).

Step 3. Each time that the lines representing the occupants touched a cell of the grid, the individual is assigned to that grid cell throughout their entire journey on the landing. Occupant ellipses in the same location can be part of as many as three different grid cells in this example.

Step 4. The actual usage of different portions of the space occupied by the evacuees is produced for each landing by counting the total number of times an ellipse touched each grid cell.

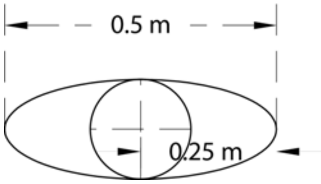


Figure 24. Occupants are modelled as ellipses of fixed dimensions.

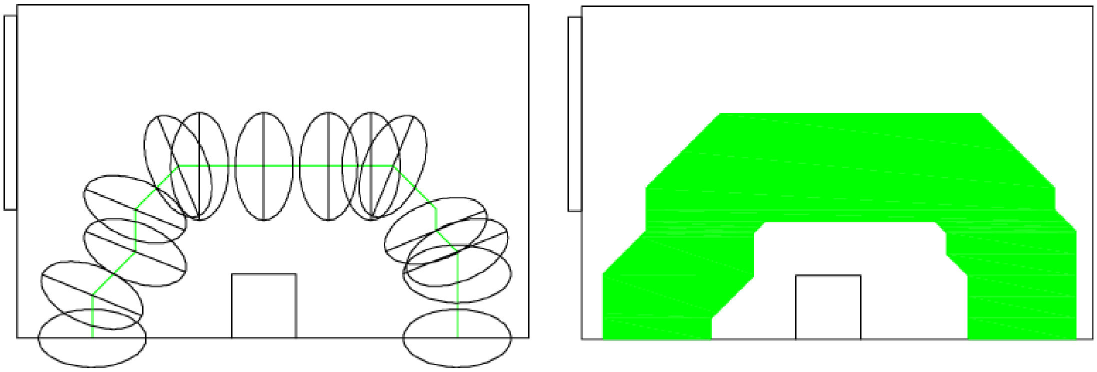


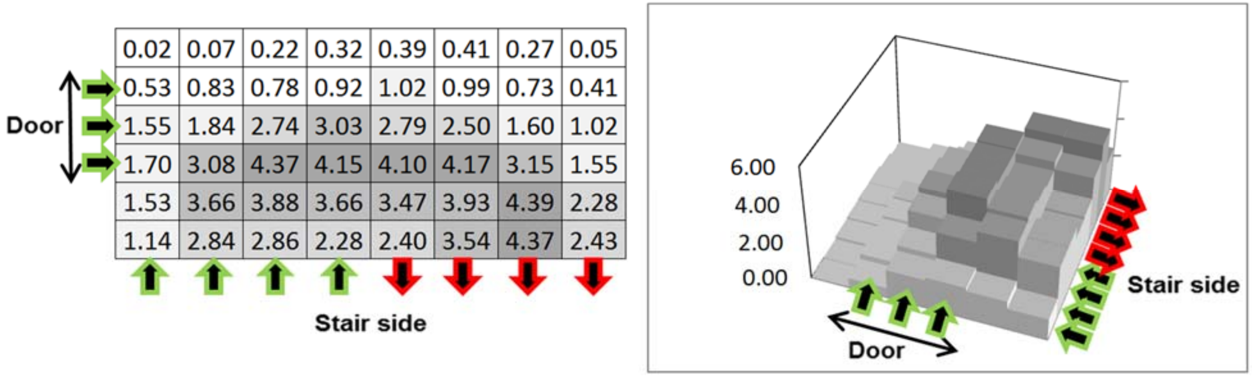
Figure 25. Reconstruction of the area occupied by one occupant within a CAD tool.

The information on the portions of the space occupied by the evacuees is used to obtain the probabilities of landing area usage. Also in this case, the probabilities can be calculated in relation to different conditions (in order to obtain conditional probabilities) such as congestion levels, merging flows, etc., producing Probable Effective Areas (PEAs). PEAs represent the probabilities associated with the usage of different grid cells, i.e. the space occupied by the evacuees during their movement. The PEAs may be represented using transparencies proportional to the probability that the occupants (shown as percentages within each element of the grid) occupy a certain portion of the space in the 2D representation. 3D histograms are also used to represent the usage of the space.

Figure 26 shows a sample set of PEAs for the two stairs in Building 12. A legend is used to present the data, i.e. transparencies are used to show PEAs (expressed in %) in proportion to the space usage (shown to the right). Arrows are used in the figures to represent the zones where occupants enter or leave the landing. Since landings present different geometrical configurations, data from the two landings are presented separately. Landings are split in individual cells of approximately 0.12 m by 0.12 m and probabilities of usage are presented in each cell. PEAs are presented for the complete sample of 215 occupants in stair A and stair B. Data for all occupants in the two different landings show a similar space usage, i.e., there are portions of the space on the outer boundary of the landings that are rarely used (see white zones in Figure 26). Additional details and analysis can be found in reference [89].

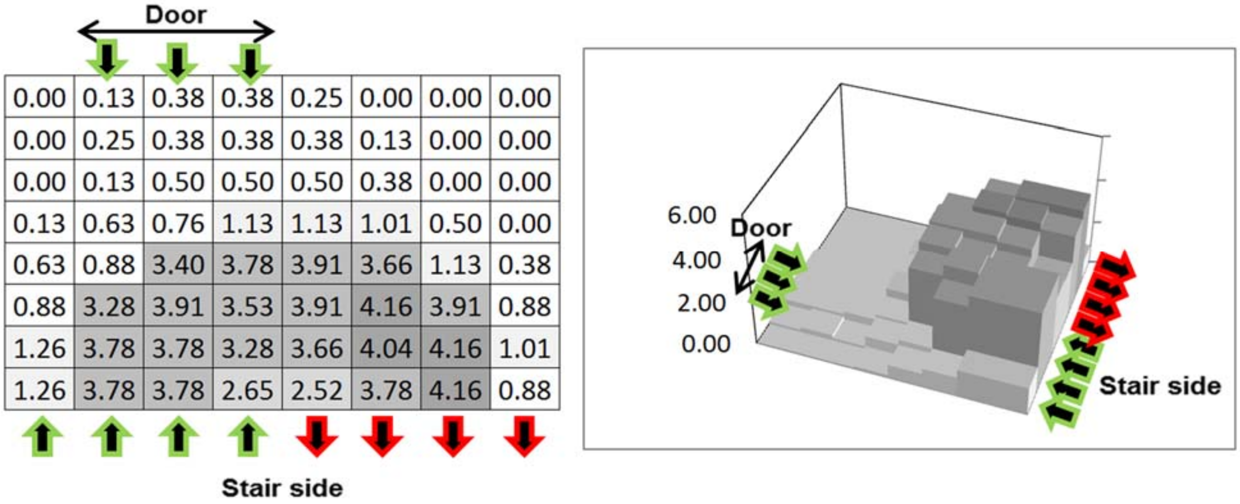
Legend
□ 0-1 %
□ 1-2 %
▨ 2-3 %
▨ 3-4 %
■ 4-5 %
■ >5 %

PEA (%) – Stair A – All occupants



0.02	0.07	0.22	0.32	0.39	0.41	0.27	0.05
0.53	0.83	0.78	0.92	1.02	0.99	0.73	0.41
1.55	1.84	2.74	3.03	2.79	2.50	1.60	1.02
1.70	3.08	4.37	4.15	4.10	4.17	3.15	1.55
1.53	3.66	3.88	3.66	3.47	3.93	4.39	2.28
1.14	2.84	2.86	2.28	2.40	3.54	4.37	2.43

PEA (%) – Stair B – All occupants



0.00	0.13	0.38	0.38	0.25	0.00	0.00	0.00
0.00	0.25	0.38	0.38	0.38	0.13	0.00	0.00
0.00	0.13	0.50	0.50	0.50	0.38	0.00	0.00
0.13	0.63	0.76	1.13	1.13	1.01	0.50	0.00
0.63	0.88	3.40	3.78	3.91	3.66	1.13	0.38
0.88	3.28	3.91	3.53	3.91	4.16	3.91	0.88
1.26	3.78	3.78	3.28	3.66	4.04	4.16	1.01
1.26	3.78	3.78	2.65	2.52	3.78	4.16	0.88

Figure 26. Example of 2D and 3D representation of PEA (expressed in percent) for all occupants of the two stairs in building 12.

5.6 Use of the Data to Inform Egress modeling

Finally, the data collected in the present study are also intended to facilitate its use in the development of stair movement algorithms in egress models or comparison with egress model results to evaluate the predictive capability of the models. This section provides a sample comparison of some of the stair data with the results of one egress model. The comparisons show that the accuracy of the predictions depends on the level of detail included in the model input that has implications both on model validation as well as the use of the data and models for performance-based design applications.

5.6.1 Network Model

EvacuatioNZ is a coarse network model being developed at the University of Canterbury in which building spaces are described by a network of nodes which are connected together by paths [92]. The advantages of a network model such as EvacuatioNZ are the ease with which simple building geometries can be created without the need for detailed CAD-like drawings or extensive user input and the relatively short computational time needed to run a simulation. For the scenarios examined in this study, typical run times were around 400 s for 40 repeated simulations (e.g. Stair 8N with 665 agents) on a regular laptop PC. Geometrical input into EvacuatioNZ can be aided with the use of a third party graphical interface called yEd [93] (version 3.11) and there is also the capability to use this third party software to generate graphical output and simple animations. Version 2.8 of the EvacuatioNZ software is used in this study.

In EvacuationNZ, nodes are defined in terms of length and width dimensions and connections are defined in terms of their length and other characteristics. Building occupants are represented as agents with their own behavioral and personal attributes. The user has the ability to randomly distribute a fixed number of agents across any defined range of specified nodes when each simulation is executed. The model includes a range of exit behavior strategies, including those that require the minimum travel distance to any ‘safe’ node or the minimum travel distance to a user-specified ‘safe’ node. The network has to have one or more ‘safe’ nodes which represent final destinations for agents. The choice of exit behavior can be probabilistically assigned to groups of agents. Pre-observation times can be represented through the use of distributions with the shape and statistics appropriately selected by the user.

The model has the ability to employ a range of distribution shapes whenever a statistical distribution can be specified for an input parameter and these distributions can be truncated at a specified upper and/or lower limit. Distributions can be uniform, normal, lognormal, and Weibull shapes.

Simulations are run over a defined time period or until all occupants (or agents) have reached a ‘safe’ node. The simulation is broken into user-specified time steps and previous benchmarking suggests that a time step of 1 s gives appropriate results.

The movement speed of agents is a function of density, stair dimensions, individual characteristics and the like. The model can set an agent's unimpeded movement speed as a function of age, sex and BMI [9] but without any other data available, the maximum walking speed is set to 1.20 m/s to correspond with Gwynne and Rosenbaum [59]. For occupant densities greater than 0.54 agents/m^2, movement speeds are modified using the equations provided in the SFPE Handbook [59] such that the relationship between speed of travel S (m/min) and occupant density D (agents per m^2) is given by

$$S = k_t\left(1 - 0.266D\right) \tag{25}$$

For level corridors or doorways, the SFPE Handbook gives $k_t = 84.0$ while the movement on stairs is adjusted for the riser and tread dimensions such that $k_t = 51.8(G/R)^{0.5}$ where G is the length of the stair tread going and R is the riser height of each step. In some of the buildings studied here the step dimensions were outside of the values given in the SFPE Handbook but it is assumed that the equation is still appropriate.

Movement in crowded conditions is based on the equations provided by Gwynne and Rosenbaum [59] such that the relationship between speed of travel and occupant density is given by a linearly decreasing function for occupant densities greater than 0.54 people/m^2. Uncongested movement speeds can be fixed by the user or determined by the use of a distribution. The model also accounts for the effect of queues at constrictions using the effective width concept [3] where a 0.15 m boundary is used for doors or stair side-walls and typically 0.09 m from the center of a stair handrail depending on the configuration. The formation of a queue will depend on the presentation rate at the constriction and it is possible that no queue will form. An agent can only move through a constriction into a path if the occupant density in the downstream node is less than a maximum occupant density specified in the model. A maximum occupant density of 2.75 agents/m^2 has been found to give suitable results in previous work [94].

5.6.2 Representation of Agents in the Simulations

In order to simulate the evacuation drills as closely as possible, the ideal situation is to have the exact number of people on each floor, their exact stair entry time, and their individual uncongested walking speed. Having this data would mean the simulations would then be assessing the capability of the model to adequately represent the stairs and the movement of the agents by minimizing other uncertainties. However since it was not practical to record or obtain this level of detail from the drills, it means the modeling has to deal with the uncertainties regarding the floors on which people started, their stair entry time etc.

On the one hand, the modeling should only consider those occupants for which sufficient data are available so that a meaningful comparison can be made. However, since the occupants that have been neglected from the modeling would have still been present in the drill and potentially affected the results, then those occupants should be simulated. Several modeling scenarios are possible:

- Randomly distribute a known number of occupants across all floors and apply a global stair entry time distribution. This approach is applied to all of the stairs considered in this study.
- Assign a known number of occupants to floors and apply a global stair entry distribution. This approach is applied to selected stairs where sufficient data are available.
- Assign each agent with the exact starting floor and stair entry time. Again this approach is applied to selected stairs where sufficient data are available.
- Agents can be distributed over lower and upper floors that were used in the drill.

As an example of the use of the data from this report, only the first scenario is presented.

In scenarios where firefighters entered the stairs, the effects of this have not been included in the modeling.

5.6.3 Representation of Stairs in Model

In order to model the stairs, the network was constructed to closely represent the actual geometry. Each floor level consists of a node to represent the floor, a node to represent the floor landing, a node to represent the mid-level landing and two nodes to represent the stair flights. Stair-type connections are used to link landing nodes with stair nodes and level-type connections to create other links (see Figure 27).

Landing travel distances are modeled as the longest dimension. Stair travel lengths are modeled using the diagonal distance calculated from the step tread and riser dimensions, and the number of steps. The effective width of the stairs was determined by having a wall / handrail boundary on the ‘outer’ edge and an open handrail on the ‘inner’ edge.

Floor nodes are arbitrarily set to 100 m by 100 m to ensure sufficient space for agents. Additional agents are set so that they are effectively positioned at the door leaving the floor so there is no traveling required. Since the information from the cameras gives the entry time of a person into a stair, then in the modeling, the connection length between the floor and its landing is 0.01 m and a 10 m wide door constriction is arbitrarily used so that no queuing occurs and agents immediately enter the landing once their stair entry delay has elapsed.

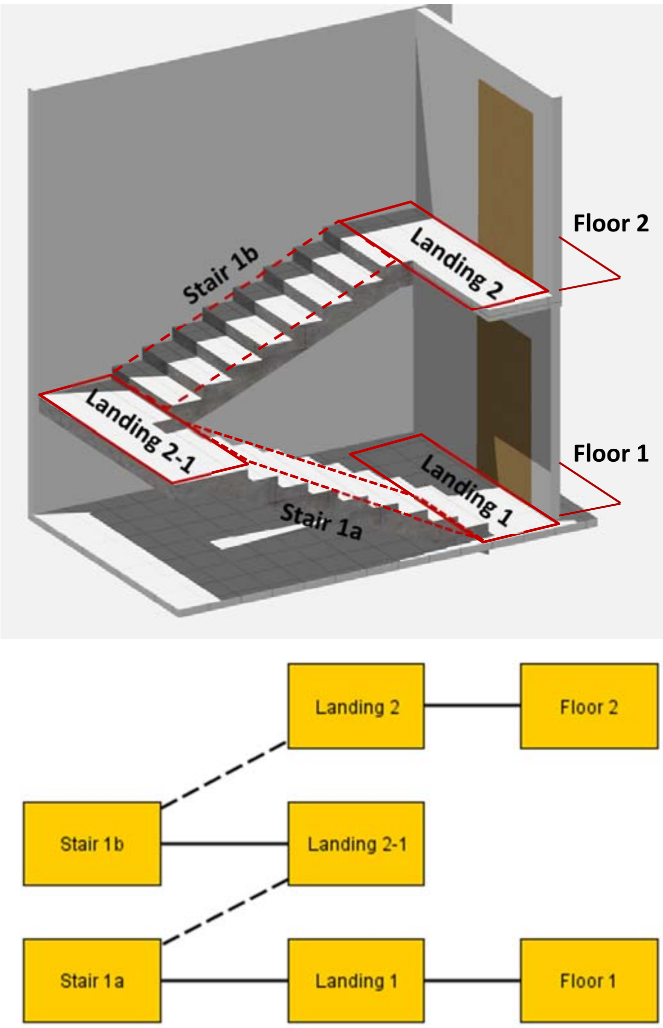


Figure 27. Sample stair geometry and representation as a series of nodes and arcs

5.6.4 Effect of stair entry time

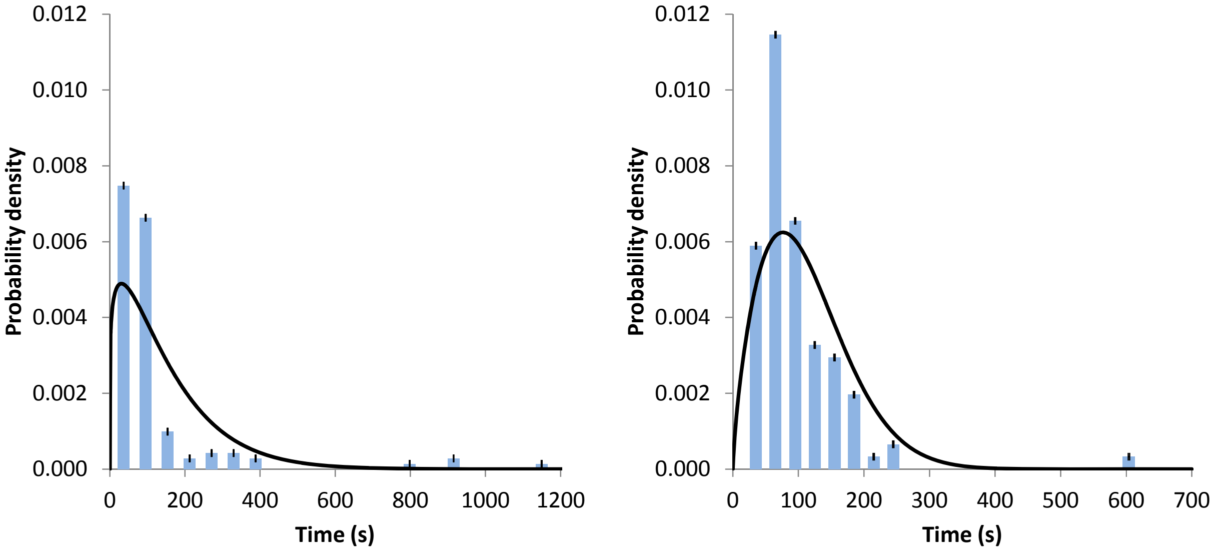
The ability of EvacuatioNZ to enable the model user to specify pre-observation time distributions is used to simulate the stair entry times. Pre-observation stair entry delays from the building data are used to estimate a distribution of stair entry times for each stair. Although some datasets do not fit any particular distribution particularly well, MacLennan et al. [95] suggest that a Weibull distribution is the most suitable way to describe the probability distribution of pre-observation times (they also note that other distributions may be equally appropriate). Therefore, the stair entry delay times are all represented by Weibull distributions for consistency with the lower bound fixed at zero (see Table 18). For later simulations, the actual starting floor location and stair entry delay times for each building occupant are also used. Table 18 also shows that three stairs in Building 7 have less than 50 % of the stair entry floor and time delay values measured, which limits comparisons with the simulations.

Table 18. Table of distributions: percentage of occupants modeled, percentage with stair entry time

Building / stair designation	Percentage of occupants with final exit time recorded	Percentage of occupants with stair entry delay time recorded	Percentage of occupants with entry floor recorded	Stair entry Weibull distribution parameters (alpha, beta)
4A	95	100	100	1.1742, 155.89
4B	97	99	100	1.7281, 126.17
5A	99	100	100	1.5229, 191.99
5B	97	100	100	1.5940, 168.41
6-5	87	100	100	1.9910, 191.61
6-5A	95	99	95	2.0847, 261.34
6-6	94	100	98[a]	2.4361, 234.33
6-6A	100	90	100	1.9133, 228.86
7-1	97	49	49[b]	1.8119, 230.85
7-3	94	99	100[b]	1.9433, 178.22
7-7	92	25	37[b]	1.4531, 237.57
7-12	99	49	49[b]	2.1499, 220.18
8N	97	99	99	1.5135, 231.33
8S	99	91	100	1.8857, 166.88

a – Stair 6-6 has 2 occupants with no stair entry time but a stair exit time that can be used to approximate their stair entry delay.

b – Entry floor not recorded, only floor on which occupants were first seen.



Stair 4A

Stair 4B

Figure 28. Measured stair entry delay times and derived Weibull distribution for Building 4.

5.6.5 Baseline Results

Table 19 and Figure 29 summarize the model predictions of total evacuation time for several of the buildings included in this report. Since the Stair 6-6 and Stair 6-6A joined on the 4th floor and it is not clear which exit occupants then used, no further analysis is reported here. For these simulations, agents are placed randomly on floors of the building with a global stair entry delay for the occupants estimated from the distributions from Table 18. Modeling results from forty simulations for each stair are shown. Additional simulations would provide better estimates of the model variations, but are sufficient for the current examples.

Figure 30 shows the measured and simulation times for 95 % of occupants to reach the exit. Excluding Building 6, there is at most a ±17 % difference between the simulations and the measured values. Simulations for Building 6 show faster simulated times of up to 26 % although, as noted previously, the data available for this building are more limited than the other buildings analyzed.

Table 19. Summary of total evacuation time from selected fire drills compared to the range of total times from simulations.

Building / Stair Designation	Total Evacuation Time (s)	Evacuation Time for 95 % of Occupants (s)	Simulated Total Evacuation Time (s)	Simulated Evacuation Time for 95 % of Agents (s)
4A	1339	564	712 ± 24	474 - 608
4B	1091	631	617 ± 23	561 - 601
5A	1026	601	666 ± 13	610 - 643
5B	841	587	584 ± 17	524 - 558
6-5	1066	838	1017 ± 55	826 - 954
6-5A	865	839	1108 ± 81	859 - 982
7-1	1032	707	736 ± 57	520 - 595
7-3	927	619	558 ± 36	466 - 519
7-7	1193	717	843 ± 33	544 - 673
7-12	612	517	600 ± 50	429 - 507
8N	1576	1043	1212 ± 11	1139 - 1189
8S	1086	922	943 ± 8	882 - 920

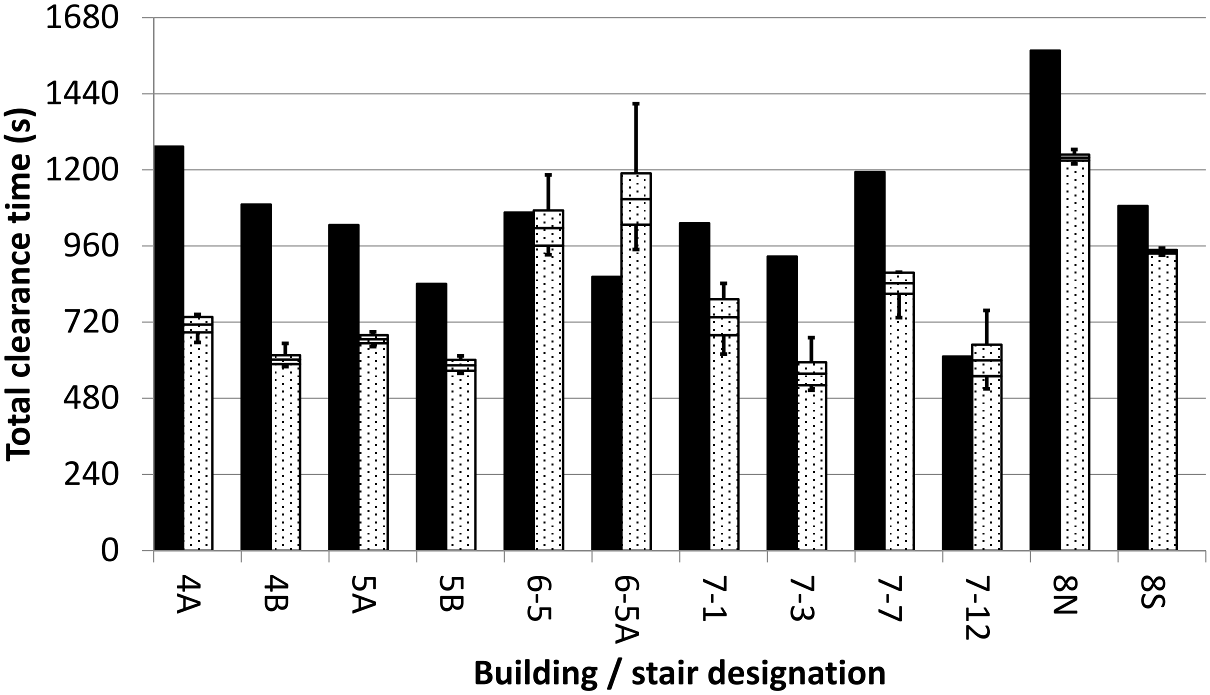


Figure 29. Total evacuation times from selected drills compared with EvacuatioNZ predictions (mean values with uncertainties expressed as one standard deviation. maximum and minimum times are shown by range bars).

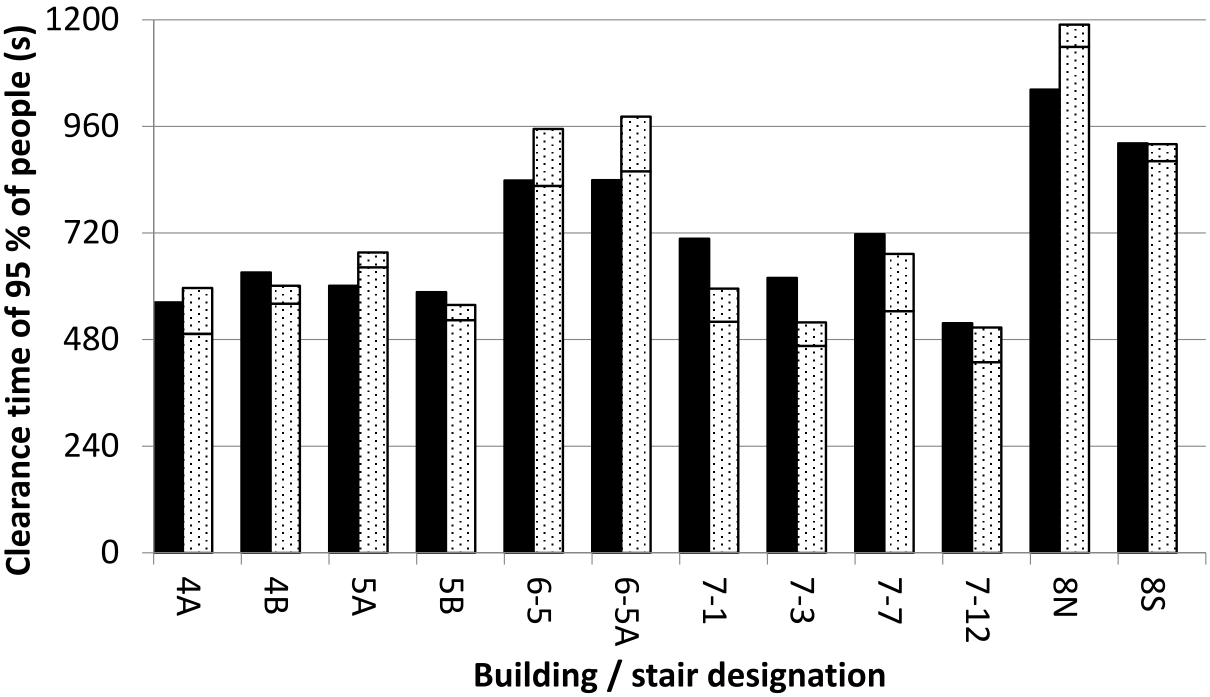
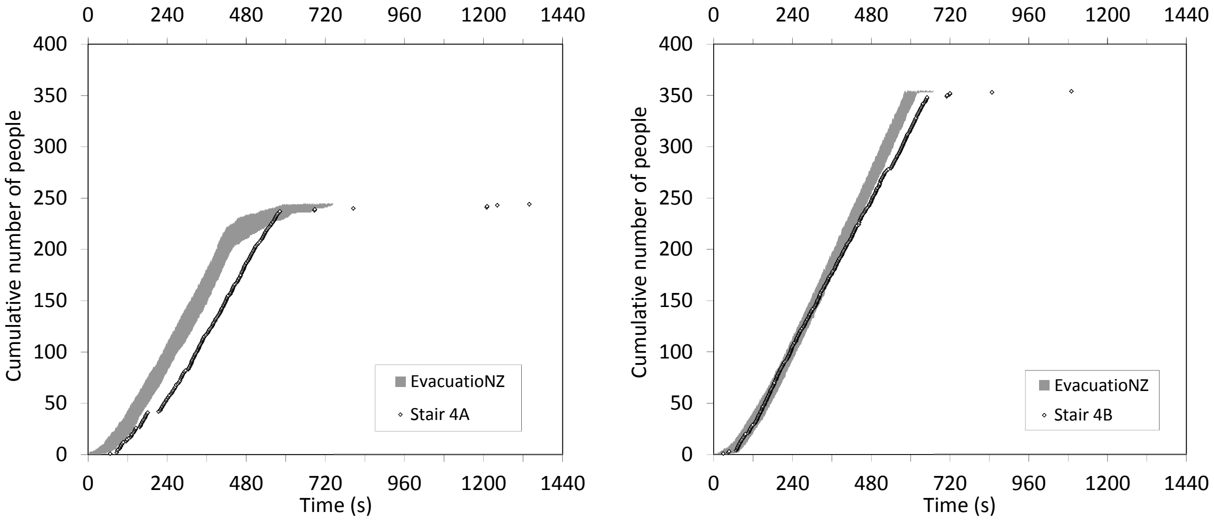


Figure 30. Evacuation times for 95 % of building occupants from selected drills compared with EvacuatioNZ predictions (maximum and minimum predicted values indicated).

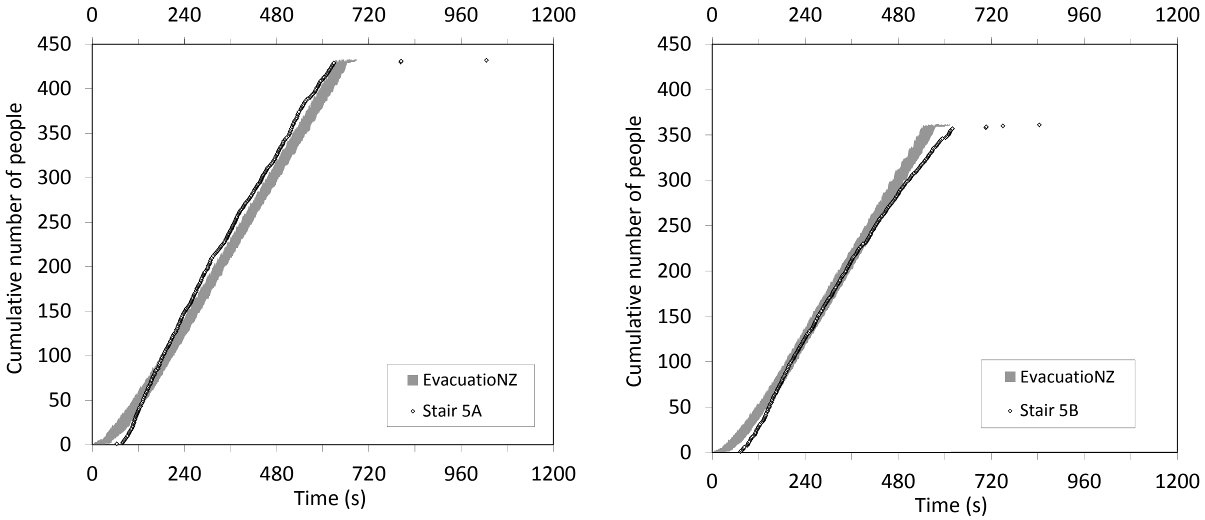
Typically, though not always, model-estimated times are much shorter than those measured in the drills. Comparison of total evacuation times from drills with simulated results has limited value as the times are influenced by the effect of a small number of people who exit the stairs at the end of the evacuation. Table 19 also includes the evacuation time for the first 95 % of building occupants which does not include these particularly late evacuees. An even more useful comparison is to examine the cumulative number of people who have exited the stairs as a function of time. Figure 31 through Figure 35 show the stair entry distribution and cumulative number of agents evacuees for several of the buildings studied.



Stair 4A

Stair 4B

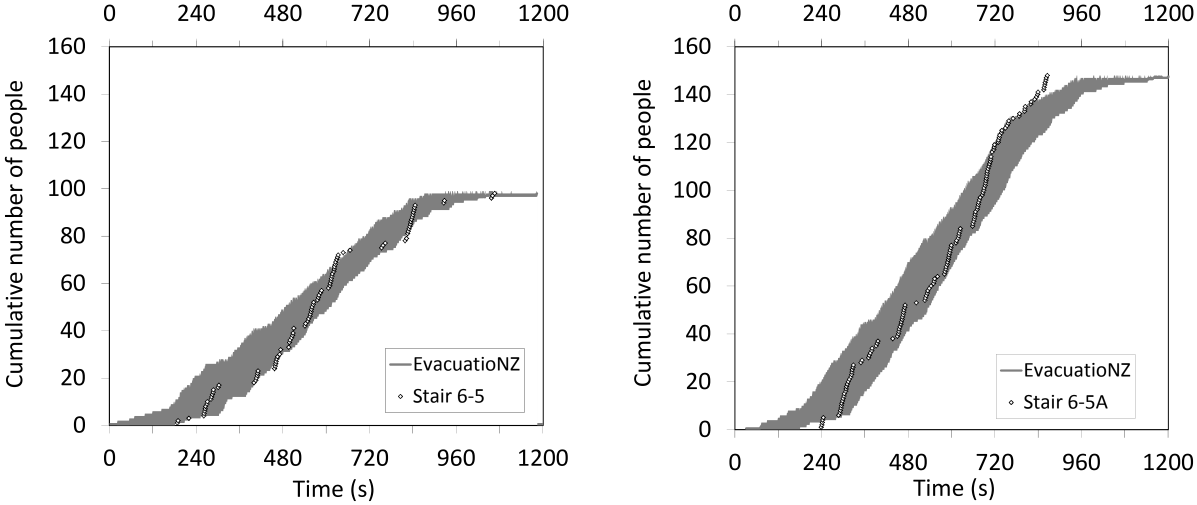
Figure 31. Cumulative number of people exiting Building 4 where simulations randomly assign floors to agents and use a global stair entry delay time.



Stair 5A

Stair 5B

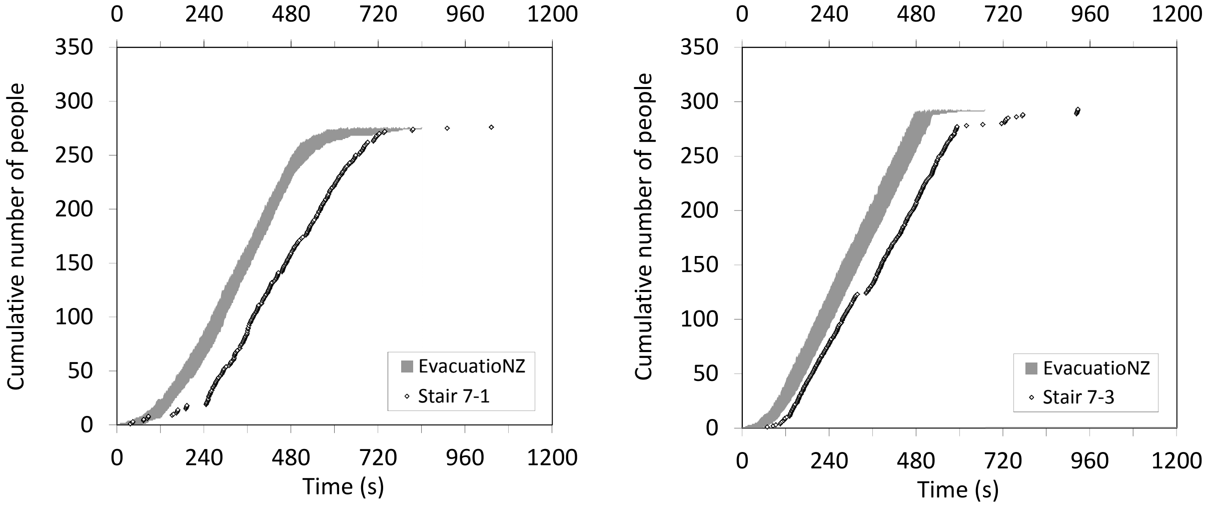
Figure 32. Cumulative number of people exiting Building 5 where simulations randomly assign floors to agents and use a global stair entry delay time.



Stair 6-5

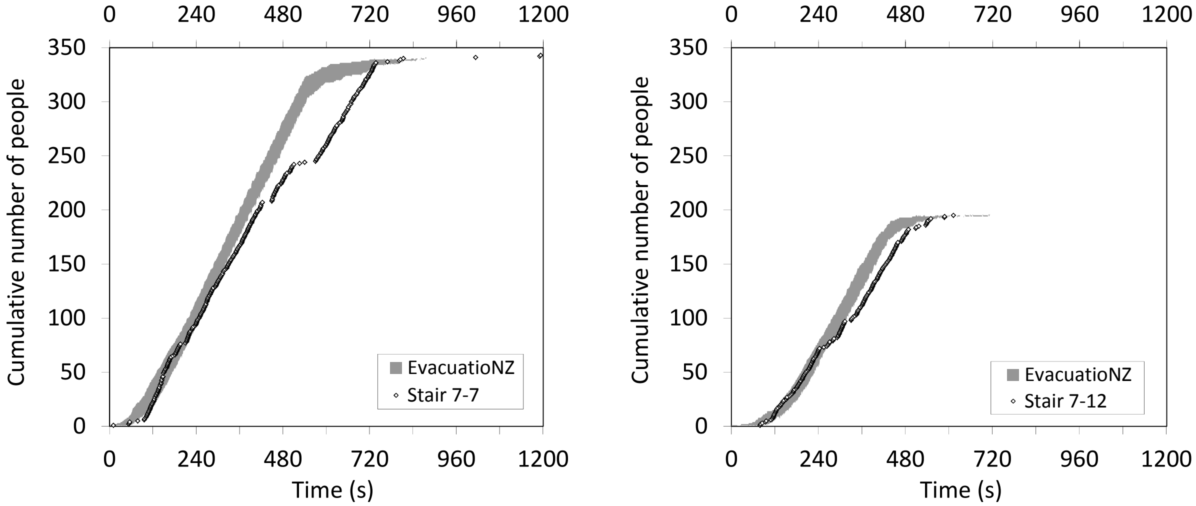
Stair 6-5A

Figure 33. Cumulative number of people exiting Stair 6-5 and Stair 6-5A where simulations randomly assign floors to agents and use a global stair entry delay time.



Stair 7-1

Stair 7-3



Stair 7-7

Stair 7-12

Figure 34. Cumulative number of people exiting Building 7 where simulations randomly assign floors to agents and use a global stair entry delay time.

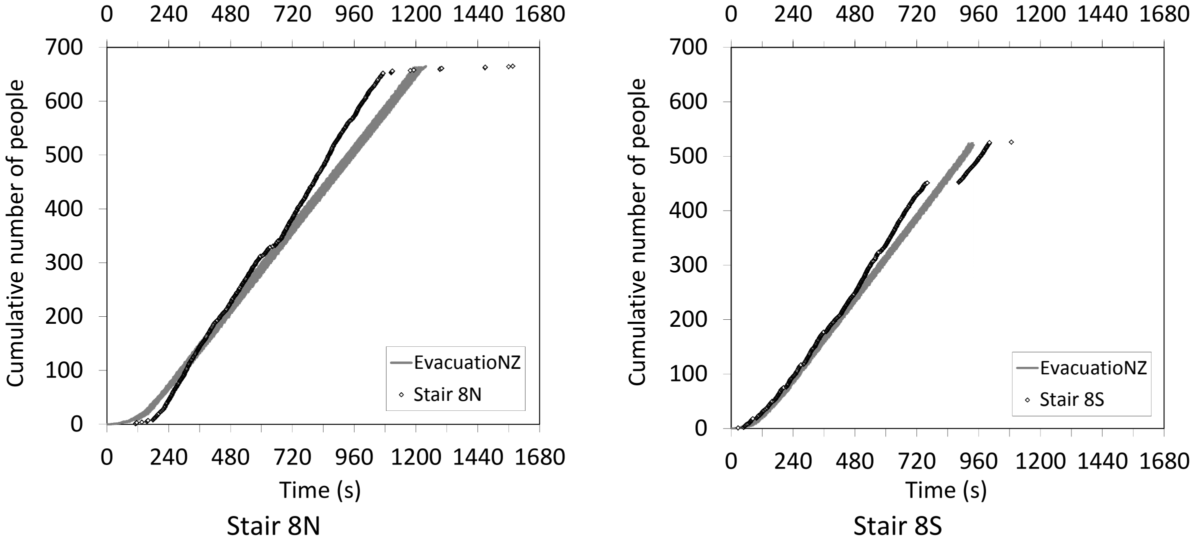


Figure 35. Cumulative number of people exiting Stair 8N and Stair 8S where simulations randomly assign floors to agents and use a global stair entry delay time.

5.6.6 Discussion

EvacuatioNZ shows qualitatively similar results to stair flows from the drills. This modeling exercise illustrates the benefits of the data collated in this study as part of any effort to benchmark the capability of egress models. The work suggests how such data may need interpretation particularly if it is to be considered within a design context and points the way to further investigations.

5.7 Discussion of Results

The Hawkes model predicts the intensity of the distribution of flow over time for each dependent variable of interest. The three parameters in the Hawkes model, μ, α, and β provide a quantitative measure of the background intensity, the likelihood of formation of clusters of occupants, and the size of these clusters during the evacuation, respectively. The model was used to estimate intensities for pre-observation time, stair travel time, and total evacuation time. The important factors that impact these times were consistent for all three of these times[27]. The number of people using the stair, building height (exit distance), and building type were found to be significant, with P values less than 0.02. For overall evacuation time, stair tread depth and height were also significant. It is notable that stair width was not found to be significant. Since stair widths in the study did not vary significantly from building to building, it is difficult to draw a strong conclusion. Still, small variations in stair width were not seen to significantly impact the flow in the stair.

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[27] For both pre-observation time and total evacuation time, the intensity is representative of the flow of occupants out the exit door at the base of the stair. For stair travel time, occupants enter the stair at different times. Thus, the intensity is indicative of the total time taken traversing the stair, but the physical significance of this intensity is not as clear as it is for pre-observation time and total evacuation time.

Clearly clustering impacts the speed of movement of occupants during building evacuation. As shown in Table 13, the branching ratio, α/β, is always less than unity, indicating some level of clustering of occupants within all of the stairs, regardless of crowding, stair width, door placement, etc. Point process modeling was able to quantify the level of interactions between occupants.

Additional research would be needed to understand the reasons for and the impact of the observed clustering in the stairs. Still, point process modeling holds promise to be able to better capture the impact of occupant interactions in future egress models.

6 Summary

This project provides a freely available set of raw data on evacuation-related people movement on stairs in the United States. The data of people movement on stairs consist of the times that each individual is observed by every video camera in every stair in every building observed by NIST (14 buildings total). Within the dataset, 11 of the 14 buildings were office buildings, and 3 buildings were residential. Of the residential buildings, two of the buildings were exclusively labeled as assisted living facilities or elderly housing, which provided valuable evacuation timing data for people with mobility impairments and elderly occupants. A total of 5244 people (at a total of 173 camera locations) were observed over the 14 NIST-observed buildings, which ranged from 6 to 62 stories in height.

Also accompanying the egress times in the database is detailed information on building and stair configuration for the buildings observed by NIST. Stair, horizontal corridor, and landing sizes throughout the building, as well as stair direction and door location from the floor into the stairs are provided. The inclusion of data on building and stair configuration allows analysts to evaluate travel distances, density, movement speeds, movement flows, and any other type of movement parameters that can be measured inside a stairway (e.g., passing behavior or merging behavior). These movement parameters can be determined for individual stairs, individual buildings, all office or residential buildings, or the entire dataset of 14 NIST-observed buildings, depending upon the types of questions analysts are required to answer.

This report has studied the typical engineering variables used to describe stair movement during building evacuations, reviewed literature values for movement speeds, and presented data from new fire drill evacuations. While the report provides information to improve the technical foundation of stair egress in building codes and data for egress model validation and development, there is also the need for additional study of stair egress. The major conclusions and needs identified by the study are summarized below.

6.1 Movement Speed

The mean movement speed for the 14 buildings evacuations studied was 0.44 m/s ± 0.19 m/s. This mean movement speed represented more than 22000 individual measurements in 30 stairs in 14 different buildings. The harmonic mean (rather than the more typical arithmetic mean) was seen as appropriate for calculating mean movement speeds for individuals traveling different distances. Details on calculating the overall mean value, mean values for each stair, and mean local movement speeds is included in Appendix B.

There was considerable variation in local movement speeds. Individual local movement speeds ranged from 0.07 m/s to 1.7 m/s. Using a distribution of movement speeds rather than a single value should provide a more realistic representation of movement speed in stairs. Characteristics of the distribution would be the subject of additional study.

People needing assistance move significantly slower than the general population. In the two buildings where most residents required assistance to evacuate using stairs (Buildings 9 and 10), the mean movement speed was 0.28 m/s ± 0.17 m/s.

Data from the current study are reasonably consistent with historical data. The use of historical data may still be appropriate within the scope and limitations of the original collection.

The flow of occupants out the exit door at the bottom of the stairs was seen to be dependent largely on the number of occupants using the stair and the height of the building. The following correlation, with an R^2 of 0.88, was found to fit the data:

$$F_{ave} = 0.42\left(\frac{P_{total}}{D_{exit}}\right)^{1/3} \tag{26}$$

where F_{ave} is the mean flow out the exit door in persons/s, P_{total} is the total number of people using the stair, and D_{exit} is the maximum distance travelled by people using the stair. This correlation was found to work well for the middle 90 % of those exiting the stairs. In all stairs, there were a small number of outliers who evacuated early and late in the evacuation. These were seen to be a combination of those with building responsibility (floors wardens or first responders, for example), those who significantly delayed beginning evacuation (but who travelled at normal speeds during their evacuation), and a limited number of particularly slow evacuees. Still, the time for the early and late evacuees can impact the overall evacuation time for a stair. On average, the early and late evacuees each account for about 20 % of the total stair evacuation time with a wide range for both. Thus, estimation of evacuation time must include the pre-evacuation time (largely, the time taken by the early evacuees), the time taken by the bulk of the evacuees (taken the middle 90 % in the analysis in this report), and the added evacuation time for late evacuees. For the latter, a design margin is typically included in the estimates.

6.2 Important Parameters that Effect Stair Egress

From regression modeling and Bayesian analysis of both the flow correlations (see section 5.3) and point process modeling (see section 5.4), the two most significant variables were the number of occupants using the stairs and the height of the building, with a clear regression between these variables and flow out of the stairs at the exit door.

Stair width did not have a statistically significant impact on occupant flow for the buildings considered in this study. These findings are the result of the fact that effective width is well correlated with two other independent variables: travel distance and total population in the stairs. Thus, while the modeling results of this research do not show a significant relationship between stair effective width and mean flow, this project is not able to definitely state that incremental increases in stair width is inconsequential to mean stair flow. Some of this may be simply because typical building design calls for increased stair capacity (typically by increased stair width) as floor population in the building increases. Another possible explanation for the contradiction in findings (on the effect of stair effective width) is the lack of variance in effective width among NIST-observed building samples. All of the buildings observed in this study are code-compliant buildings with effective stair widths ranging from 756 mm (29.75 in) to 1232 mm (48.5 in), with the majority (62 %) of stairs falling within the narrow range of 729 mm (28.7 in) to 813 mm (32 in).

6.3 Techniques for Improved Egress modeling

In addition to providing data on occupant movement in stair egress, the report also included more detailed analysis of path selection and clustering. Implications of these analyses on egress modeling are summarized below.

A detailed analysis of some of the data (see section 5.5) showed that both variation of movement speeds and path selection can be successfully described with a single parameter distribution for a base path.

Sample comparisons of the data to an existing egress model demonstrate the usefulness of the data for model validation. These comparisons show that the level of detail in the model inputs can have a significant impact on the quality of the predictions. Additional analysis of the data would help better define the necessary range of inputs and their appropriate use in a range of egress models.

Point process modeling was seen as a promising technique to quantitatively account for clustering of occupants during stair egress. Use of the Hawke's point process model showed a consistent measure of clustering in all of the stairs, regardless of crowding, stair width, door placement, etc. Additional study would be required to better understand its applicability to egress modeling.

6.4 Implications of the Data for Building Code Requirements

One of the main objectives of this report was to advance the technical foundation to life safety-related codes and standards for buildings. As mentioned earlier in this report (see Section 2.3), the International Building Code (IBC) [51] and NFPA's Life Safety Code (LSC) [52] provide requirements for buildings in terms of capacity and usability. Capacity requirements ensure that the stairways are sized to allow the prescribed number of occupants (often referred to as the design load) to use the stairs in a timely manner. Usability requirements, on the other hand, ensure that the stairway construction does not impede safe use of the stairway.

Stair Width: In terms of the capacity requirements, both the IBC and the LSC directly correlate incremental increases in stair width with increased capacity. More specifically, stair capacity factors (i.e., 5 mm (0.2 in) of required stair width per person on an occupied floor in the building) are used to calculate a required stair width (with a minimum stair width specified as 1118 mm (44 in) wide in both the IBC and the LSC[28]. The LSC further requires an increase in

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[28] The minimum requirement exists for stairways serving greater than 50 people, and less than 2000 people in the LSC.

the minimum stair width to 1422 mm (56 in) for buildings serving equal to or greater than 2000 people).

Using point process modeling, this research tested the influence of effective width on stair efficiency, measured here as increased stair flow. Stair flow was measured at the bottom of the stairs, located at the exit door from the stair. However, since there was no queuing witnessed at these stair doors in each stairway observed, the effective width used for analysis of stair efficiency was the stair's effective width. The results of the Hawkes model showed that incremental increases in stair width did not show a statistically significant increase in mean stair flow across our building sample.

The contradiction in these findings is likely the result of the fact that effective width is well correlated with two other independent variables: travel distance and total population in the stairs. Thus, while the point process modeling results of this research do not show a significant relationship between stair effective width and mean flow, this study is not able to definitely state that incremental increases in stair width is inconsequential to mean stair flow.

Number of People: Currently, egress capacity (i.e., stair width) is calculated based upon the number of people *from a floor* required to use that stair (using IBC/NFPA codes). The focus on the number of occupants from a particular floor shows that the codes design for phased or partial evacuation only (i.e., where only a section of the building evacuates or relocates to another section in the building), rather than for full building evacuation. However, NIST's study of the World Trade Center Investigation recommended a focus on full building evacuations; stating the "NIST recommends that tall buildings be designed to accommodate timely full building evacuation of occupants when required in building-specific or large-scale emergencies…" of which fire is one [9].

The results of this study show the total exit time for middle 90 % is linear to the number of floors provided the floors have the same travel distance to the next floor and the same population per floor. In all stairs, there were a small number of outliers who evacuated early and late in the evacuation. These were estimated to add an average of 22 % to the total evacuation time with a range as high as 61 %.

Tread Depth and Riser Height: In terms of the usability requirements, one of the factors considered in the analysis of stair efficiency was the riser and tread step measurements. The IBC and the LSC state that stair riser heights shall be 178 mm (7 in) maximum and 102 mm (4 in) minimum, and rectangular tread depths shall be 279 mm (11 in) minimum[29].

The results of this study show that the steeper and longer stairs positively impacted the flow; i.e., the upper limits of stair riser and tread design in the NIST-observed sample provided higher flow rates on the stairs during evacuation. Within the NIST data, the riser heights of stairs ranged from 150 mm (5.9 in) to 198 mm (7.8 in) in height and the tread depths of stairs ranged from 241 mm (9.5 in) to 305 mm (12 in) in length. The findings of this study suggest that stair

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[29] The IBC also provides specifics on the ways in which to measure these values: the riser heights are measured vertically between the nosings of adjacent treads, and the tread depths are measured horizontally between the vertical planes of the foremost projection of adjacent treads and at a right angle to the tread's nosings.

configurations on the upper range of the code required riser heights (approximately 180 mm to 200 mm [7 to 7.8 inches]) and the minimum range of the code required tread depths (approximately 305 mm [12 in]) increase the stairway flow during a full building evacuation.

For safe movement on stairs, to suit both ascent and descent, Templer suggests that risers be constructed between 160 mm and 183 mm (6.3 in and 7.2 in) and tread depth be at least 280 mm (11 in) wide [67]. According to his study, a 280 mm (11 in) minimum wide tread depth account for most foot and shoe sizes in this country. Additionally, risers from 117 mm to 183 mm (4.6 in to 7.2 in) had the fewest number of missteps associated with them. While values in the current study for riser height slightly exceed those suggested by Templer, the values generally similar to those of Templer. Additionally, since the current study observed evacuation on stairs with a minimal range of variance, it was impossible to discover benefits of riser heights or tread depths that fell outside of the current range.

6.5 Additional Research Needs

This report provides just a beginning in understanding the additional human behavior-related factors that impact movement beyond classic hydraulic calculation-based variables. Additional research is needed to better understand these factors, including the following:

- To fully understand overall exit times for building egress, a better understanding of movement and behavior of occupants prior to entering the stairs is required. This report presented a simple analysis of the time occupants take to arrive at the stair for egress. No data was collected in this study of occupant movements prior to entering the stairs.
- Additional data on movement speeds, particularly in taller buildings and with various stair widths are needed to better understand the important variables that impact stair movement speeds, particularly the impact (or lack thereof) of effective stair width on movement speed.
- Additional analysis of stair movement data to determine the best values and distributions for egress model inputs would facilitate modeling and help understand additional data needs through use of the data. Of particular interest is the impact of late evacuees on the overall evacuation time.
- Additional analysis of stair movement data using the Hawke’s point process model would help clarify clustering in stair movement and its impact on occupant flow.
- Further analysis is needed to fully understand whether fatigue occurs during building evacuations, and if so, the factors that impact fatigue, including distance traveled, age, physical ability, fitness level, etc. Additionally, if fatigue is present in certain conditions during building evacuations, it will be important to understand its impact on occupant movement speeds and flow.
- Additional analysis of merging behavior is needed, including an understanding of the proportion of stair users versus occupants entering the stairs for a variety of building scenarios (i.e., building type, occupant type, scenario type, etc.).
- Additional data collection and analysis of early and late evacuees is needed to better understand the impact of very slow evacuees on the overall evacuation time in buildings.

- Analysis of the evacuation timing of stairs versus elevators is needed, including the benefits of evacuation via elevators for different types and heights of buildings.
- Data collection and analysis of behavioral data before and during stair evacuation as well as elevator evacuation is needed. This includes additional information on the movement of occupants with mobility impairments on stairs and other building egress components.
- Since all of the analyses in this report are based on fire drill evacuations, additional research on the similarities or differences between these evacuations and real fire emergencies is needed to place the results in context.

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References

1. Hall, J.R., Jr., *The Total Cost of Fire in the United States*. 2011, Quincy, MA: National Fire Protection Association
2. Lord, J.B., et al., *Guide for evaluating the predictive capabilities of computer egress models*. 2005, GCR 06-886, Gaithersburg, MD: National Institute of Standards and Technology
3. Proulx, G., *The Evacuation Timing*, in *The SFPE Handbook of Fire Protection Engineering*, P.J. DiNenno, et al., Editors. 2002, Society of Fire Protectino Engineers: Bethesda, MD.
4. *Summary of the NIST/GSA Cooperative Research on the Use of Elevators During Fire Emergencies*, ed. R.D. Peacock. 2009, Technical Note 1620, Gaithersburg, MD: National Institute of Standards and Technology
5. Kuligowski, E.D. and B.L. Hoskins, *Analysis of Occupant Behavior During a High-rise Office Building Fire*, in *Pedestrian and Evacuation Dynamics 2010*, R.D. Peacock, E.D. Kuligowski, and J.D. Averill, Editors. 2012, Springer: Gaithersburg, MD.
6. Bryan, J.L., *An Examination and Analysis of the Human Behavior in the MGM Grand Hotel Fire*. 1983, Quincy, MA: National Fire Protection Association
7. Fahy, R. and G. Proulx, *Human Behavior in the World Trade Center Evacuation*, in *Fire Safety Science -- Proceedings of the Fifth International Symposium*, Y. Hasemi, Editor. 1997. p. 713-724.
8. Brennan, P., *Timing Human Response in Real Fires*, in *Fire Safety Science -- Proceedings of the Fifth Internaitonal Symposium*, Y. Hasemi, Editor. 1997. p. 807-818.
9. Averill, J.D., et al., *Occupant Behavior, Egress, and Emergency Communication. Federal Building and Fire Safety Investigation of the World Trade Center Disaster*. 2005, NIST NCSTAR 1-7, Gaithersburg, MD: National Institute of Standards and Technology
10. Averill, J.D., R.D. Peacock, and E.D. Kuligowski, *Analysis of the Evacuation of the World Trade Center Towers on September 11, 2001.* Fire Technology, 2013. **49**(1): p. 37-63.
11. Kuligowski, E.D., R.D. Peacock, and J.D. Averill, *Modeling the Evacuation of the World Trade Center Towers on September 11, 2001.* Fire Technology, 2013. **49**(1): p. 65-81.
12. Peacock, R.D., J.D. Averill, and E.D. Kuligowski, *Egress from the World Trade Center Towers on September 11, 2001.* Fire Technology, 2013. **49**(1): p. 7-35.
13. Proulx, G., J.C. Latour, and J.W. McLaurin, *Housing Evacuation of Mixed Abilities Occupants*. 1994, Internal Report 661, Ottawa: National Research Council Canada
14. Proulx, G., et al., *Housing Evacuation of Mixed Abilities Occupants in Highrise Buildings*. 1995, Internal Report 706, Ottawa: National Research Council Canada
15. Proulx, G. and N. Bénichou, *Evacuation Movement in Photoluminescent Stairs*, in *Pedestrian and Evacuation Dymanics 2008*, W.W.F. Klingsch, et al., Editors. 2008, Springer: Wuppertal, Germany. p. 25-42.
16. Proulx, G., et al., *Evaluation of the Effectiveness of Different Photoluminescent Stair Installations for the Evacuation of Office Building Occupants*. 2007, Research Report 232, Ottawa: National Research Council Canada

17. Gwynne, S.M.V., *Optimizing Fire Alarm Notification for High Risk Groups: Notification Effectiveness for Large Groups*. 2007, Quincy, MA: Fire Protection Research Foundation. pp. 132
18. Purser, D.A. and A.J.T. Raggio, *Behaviour of Crowds when Subjected to Fire Intelligence*. 1995, CR 143/95, Garston, Watford, UK: Building Research Establishment
19. Gwynne, S.M.V. and D.L. Boswell, *Pre-evacuation Data Collected from a Mid-rise Evacuation Exercise.* Journal of Fire Protection Engineering, 2009. **19**(1): p. 5-29.
20. Sharma, S.B., et al., *A Comprehensive Modern Approach to Developing Evacuation Data Capture/analysis and Simulation Tools for Real World Fire Engineering*, in *Proceedings of Fourth International Symposium on Human Behaviour in Fire*. 2009, Interscience Communications: Cambridge. p. 195-206.
21. Proulx, G. and J. Pineau, *Differences in the Evacuation Behaviour of Office and Apartment Building Occupants*, in *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting*. 1996, Human Factors and Ergonomics Society.
22. Shields, T.J., K.E. Boyce, and G.W.H. Silcock, *Towards the Characterization of Large Retail Stores*, in *Proceedings of the 1st International Symposium on Human Behaviour in Fire*. 1998, Text-Flow, Ltd.
23. Shields, T.J. and K.E. Boyce, *A Study of Evacuation from Large Retail Stores.* Fire Safety Journal, 2000. **35**(1): p. 25-49.
24. Christoffersen, B. and C. Söderlind, *Comparison of Two Egress Models and a Full-scale Experiment*, in *Proceedings of the fourth international symposium on human behaviour in fire*. 2009, Interscience Communications: Cambridge. p. 573-578.
25. Shields, T.J., K.E. Boyce, and N. McConnell, *The Behaviour and Evacuation Experiences of WTC 9/11 Evacuees with Self-Designated Mobility Impairments.* Fire Safety Journal, 2009. **44**: p. 881-893.
26. Galea, E.R., et al., *The UK WTC 9/11 Evacuation Study: an Overview of the Methodologies Employed and Some Analysis Relating to Fatigue, Stair Travel Speeds and Occupant Response Times*, in *Proceedings of the Fourth International Symposium on Human Behaviour in Fire*. 2009, Interscience Communications: Cambridge. p. 27-40.
27. Pauls, J.L., *Evacuation Drill Held in the BC Hydro Building 26 June 1969*. 1971, Building Research Report 80, Ottawa: National Research Council Canada
28. Pauls, J.L. and B.K. Jones, *Building Evacuation: Research Methods and Case Studies*, in *Fires and Human Behaviour*, D. Cantor, Editor. 1980, John Wiley & Sons: New York. p. 227-249.
29. Proulx, G., *Evacuation Time and Movement in Apartment Buildings.* Fire Safety Journal, 1995. **24**(3): p. 229-246.
30. Proulx, G., A. Kaufman, and J. Pineau, *Evacuation Times and Movement in Office Buildings*. 1996, Internal Report 711, Ottawa: National Research Council Canada
31. Shields, T.J., et al., *The Impact of a Wheelchair Bound Evacuee on the Speed and Flow of Evacuees in a Stairway during an Uncontrolled Unannounced Evacuation.* Journal of Applied Fire Science, 1998. **7**(1): p. 29-39.
32. Proulx, G., et al., *Assessment of Photoluminescent Material During Office Occupant Evacuation*. 1999, Ottawa: National Research Council Canada
33. Khisty, C.J., *Pedestrian Flow Characteristics on Stairways During Disaster Evacuation.* Transportation Research Record, 1985. **1047**: p. 97-102.

34. Hostikka, S., et al., *Evacuation Experiments in Offices and Public Buildings*. 2007, Working Papers 85: VTT Technical Research Centre of Finland
35. Pauls, J.L., *Building Evacuation: Research Findings and Recommendations*, in *Fires and Human Behaviour*, D. Cantor, Editor. 1980, John Wiley & Sons: New York. p. 251-275.
36. Kagawa, M., S. Kose, and Y. Morishita, *Movement of People on Stairs During Fire Evacuation Drill-Japanese Experience in a Highrise Office Building*, in *Fire Safety Science: Proceedings of the First International Symposium*. 1985: Gaithersburg, MD. p. 553-540.
37. Fruin, J.J., *Pedestrian Planning and Design*. Revised Edition ed. 1987, Mobile, AL: Elevator World.
38. Tanaboriboon, Y. and J.A. Guyano, *Analysis of Pedestrian Movements in Bangkok.* Transportation Research Record, 1991. **1294**: p. 52-56.
39. Lee, J.Y.S. and W.H.K. Lam, *Variation of Walking Speeds on a Unidirectional Walkway and on a Bidirectional Stairway.* Transportation Research Record, 2006. **1982**: p. 122-131.
40. Ye, J., et al., *Walking Behavior and Pedestrian Flow Characteristics for Different Types of Wlaking Surfaces.* Transportation Research Record, 2008. **2048**: p. 43-51.
41. Standards, N.B.o., *Design and Construction of Building Exits*. 1935, Miscellaneous Publication M151, Washington DC: National Bureau of Standards
42. Buildings, J.C.o.F.G.o., *Precautions Relating to Personal Safety*. Fire Grading of Buildings. Part III. 1952, Post-war Building Studies Number 29, Great Britain: Ministry of Works. 22-95
43. Frantzich, H., *A Model for Performance-Based Design of Escape Routes*. 1994: Lund Institute of Technology
44. Frantzich, H., *Study of Movement on Stairs during Evacuation Using Video Analysis Techniques*. 1996: Lund Institute of Technology
45. Boyce, K.E., T.J. Shields, and G.W.H. Silcock, *Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline.* Fire Technology, 1999. **35**(1): p. 51-67.
46. Wright, M.S., G.K. Cook, and G.M.B. Webber, *The Effects of Smoke on People's Walking Speeds Using Overhead Lighting and Wayguidance Provision*, in *Human Behavior in Fire, Proceedings of the Second International Symposium*. 2001: Cambrdge, MA.
47. Fujiyama, T. and N. Tyler, *An Explicit Study on Walking Speeds of Pedestrians on Stairs*, in *Tenth International Conference on Mobility and Transport for Elderly and Disabled People*. 2004: Hamamatsu, Japan.
48. Galea, E.R., G. Sharp, and P.J. Lawrence, *Investigating the Representation of Merging Behavior at the Floor-Stair Interface in Computer Simulations of Multi-Floor Building Evacuations.* Journal of Fire Protection Engineering, 2008. **18**(4): p. 291-316.
49. Boyce, K.E., D.A. Purser, and T.J. Shields, *Experimental studies to investigate merging behaviour in a staircase.* Fire and Materials, 2012. **36**: p. 383-398.
50. Peacock, R.D., B.L. Hoskins, and E.D. Kuligowski, *Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories.* Safety Science, 2012. **50**(8): p. 1655-1664.
51. International Code Council, *2012 International Building Code*. 2012, International Code Council: Washington DC.

52. National Fire Protection Association, *Life Safety Code*. 2012, National Fire Protection Association: Quincy, MA.
53. Kuligowski, E.D., R.D. Peacock, and B.L. Hoskins, *Review of Building Evacuation Models*. Second Edition ed. 2010, Technical Note 1680, Gaithersburg, MD: National Institute of Standards and technology
54. Gwynne, S.M.V., et al., *A review of the methodologies used in the computer simulation of evacuation from the built environment.* Building and Environment, 1999. **34**(6): p. 741-749.
55. Ronchi, E. and D. Nilsson, *Modelling total evacuation strategies for high-rise building evacuations.* Building Simulation, 2013. **7**(1): p. 73-87.
56. Hoskins, B.L., *The Effects of Interactions and Individual Characteristics on Egress Down Stairs*, in *Department of Fire Protecction Engineering*. 2011, University of Maryland: College Park MD.
57. Pauls, J.L., *The Movement of People in Buildings and Design Solutions for Means of Egress.* Fire Technology, 1984. **20**(1): p. 27-47.
58. Predtechenskii, V.M. and A.I. Milinskii, *Planning for Foot Traffic Flow in Buildings*. 1978, New Delhi: Amerind Publishing Co.
59. Gwynne, S.M.V. and E.R. Rosenbaum, *Employing the Hydraulic Model in Assessing Emergency Movement*, in *The SFPE Handbook of Fire Protection Engineering*, P.J. DiNenno, et al., Editors. 2008, Society of Fire Protectino Engineers: Bethesda, MD.
60. Nelson, H.E. and F.W. Mowrer, *Emergency Movement*, in *The SFPE Handbook of Fire Protection Engineering*, P.J. DiNenno, et al., Editors. 2002, Society of Fire Protectino Engineers: Bethesda, MD.
61. Nilsson, D., *Computer modeling of evacuation and fire. An inventory of three approaches* 2007, Report 3142: Lund University
62. Chooramun, N., *Implementing a hybrid spatial discretisation within an agent based evacuation model*. 2011, University of Greenwich.
63. Organization, I.M., *Guidelines for Evacuation Analysis for New and Existing Passenger Ships*. 2007, International Maritime Organization: London.
64. Ronchi, E., P.A. Reneke, and R.D. Peacock, *A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling.* Fire Technology, 2013.
65. Ronchi, E. and D. Nilsson, *Fire Evacuation in High-rise Buildings: a Review of Human Behaviour and Modelling* 2013, 3166: Lund University
66. Spearpoint, M. and H.A. MacLennan, *The effect of an ageing and less fit population on the ability of people to egress buildings.* Safety Science, 2012. **50**: p. 1675-1684.
67. Templer, J.A., *The Staircase: Studies of Hazards, Falls and Safer Design*. 1992, Cambridge MA: MIT Press.
68. Hoskins, B.L. and J.A. Milke, *Differences in Measurement Methods for Travel Distance and Area for Estimates of Occupant Speed on Stairs.* Fire Safety Journal, 2012. **48**: p. 49-57.
69. Kuligowski, E.D. and D.S. Mileti, *Modeling pre-evacuation delay by occupants in World Trade Center Towers 1 and 2 on September 11, 2001.* Fire Safety Journal, 2009. **44**(4): p. 487-496.
70. Melinek, S.J. and S. Booth, *an Analysis of Evacuation Times and the Movement of Crowds in Buildings,"* 1975, Current Paper 96/75, Garston, Watford, UK: Building Research Establishment

71. Pauls, J.L., *Demographic Changes Leading to Deterioration of Pedestrian Capabilities Affecting Safety and Crowd Movement*, in *TRB 87th Annual Meeting Compendium of Papers DVD*. 2008, Transportation Research Board: Washington DC.
72. Kuligowski, E.D., et al., *Evacuation of people with disabilities on stairs*, in *Fifth International Symposium on Human Behaviour in Fire*. 2012, Interscience Communications: Cambridge UK. p. 315-327.
73. Kuligowski, E.D., et al., *Stair Evacuation of Older Adults and People with Mobility Impairments.* Fire Safety Journal, 2013. **62**(C): p. 230-237.
74. Kuligowski, E.D., et al., *Stair Evacuation of People with Mobility Impairments.* Fire and Materials, 2014.
75. Adams, A.P.M. and E.R. Galea, *An Experimental Evaluation of Movement Devices Used to Assist People with Reduced Mobility in High-Rise Building Evacuations*, in *Pedestrian and Evacuation Dynamics 2010*, R.D. Peacock, E.D. Kuligowski, and J.D. Averill, Editors. 2012, Springer: Gaithersburg, MD.
76. Pauls, J.L., *Building Evacuation and Other Fire Safety Measures: Some Research Results and their Application to Building Design, Operation, and Regulation*, in *Man-Environment Interactions: Evaluations and Applications – The State of the Art in Environmental Design Research*, D.H. Carson, Editor. 1974. p. 147-168.
77. Cinlar, E., *Introduction to Stochastic Processes*. 1975, Englewood Cliffs NJ: Prentice-Hall.
78. Daley, D.J. and D. Vere-Jones, *An Introduction to the Theory of Point Processes*. 2003, New York: Springer-Verlag.
79. Hawkes, A.G., *Point Spectra of Some Mutually Exciting Point Processes.* Journal of the Royal Statistical Society, Series B, 1971. **33**: p. 438-443.
80. Ogata, Y., *Space-time point-process models for earthquake occurrences.* Annals of the Institute of Statistical Mathematics, 1998. **50**: p. 379-402.
81. Ogata, Y., *Seismicity Analyses through Point-process Modeling: A Review.* Pure and Applied Geophysics, 1999. **155**.
82. Baker, M.D., *Observed Behavior of Platoon Dynamics During High-Rise Stair Evacuations*, in *Department of Fire Protection Engineering*. 2012, University of Maryland: College Park MD.
83. Ronchi, E. and M. Kinsey, *Evacuation models of the future. Insights from an online survey on user's experiences and needs*, in *Advanced Research Workshop Evacuation and Human Behaviour in Emergency Situations EVAC11*, J. Capote, Editor. 2011: Santander, Spain. p. 145-155.
84. Averill, J.D., *Five Grand Challenges in Pedestrian and Evacuation Dynamics*, in *Pedestrian and Evacuation Dynamics 2010*, R.D. Peacock, E.D. Kuligowski, and J.D. Averill, Editors. 2012, Springer: Gaithersburg, MD. p. 1-11.
85. Fraser-Mitchell, J.N., *Modeling Human Behavior within the Fire Risk Assessment Tool CRISP.* Fire and Materials, 1999. **23**(6): p. 349-355.
86. Capote, J., et al., *A Stochastic Approach for Simulating Human Behaviour During Evacuation Process in Passenger Trains.* Fire Technology, 2012. **48**(4): p. 911-925.
87. Ronchi, E., et al., *A probabilistic approach for the analysis of evacuation movement data.* Fire Safety Journal, 2014. **63**: p. 69-78.

88. Nilsson, D. and R. Petersson, *Evaluation of video analysis techniques for emergency scenarios. [In Swedish: Utvärdering av videoanalysmetoder för utrymning med tillämpning på horn]*. . 2008, Technical Report 5256: Lund University
89. Ronchi, E., et al., *An analysis of evacuation travel paths on stair landings by means of conditional probabilities.* Fire Safety Journal, 2014. **65**: p. 30-40.
90. Korhonen, T. and S. Hostikka, *Fire Dynamics Simulator with Evacuation: FDS+Evac Technical Reference and User's Guide. FDS 5.5.3, Evac 2.3.1*. 2009, Working Papers 119: VTT Technical Research Centre of Finland
91. Thompson, P.A. and E.W. Marchant, *A Computer Model for the Evacuation of Large Building Populations.* Fire Safety Journal, 1995. **24**: p. 131-148.
92. *EvacuatioNZ.* [cited 2014 May]; Available from: http://www2.civil.canterbury.ac.nz/spearpoint/evacuationz/home.html.
93. *yWorks*. [cited 2012 March]; Available from: http://www.yworks.com/en/index.html.
94. Spearpoint, M., *Comparative Verification Exercises on a Probabilistic Network Model for Building Evacuation.* Journal of Fire Sciences, 2009. **27**(5): p. 409-430.
95. MacLennan, H.A., M.A. Regan, and R. Ware, *An engineering model for the estimation of occupant pre-evacuation and/or response times and the probability of their occurrence*, in *Proceedings of the 1st International Symposium on Human Behaviour in Fire*. 1998, Text-Flow, Ltd. p. 13-29.

A. Building Details

This appendix provides additional details on the geometry and data collection for the 14 buildings included in the study. Although included largely for reference purposes, it provides additional details of the buildings and stairwells evaluated to make the data widely useful.

A.1 Building 1

Building 1 is a six-story office building with seven wings located on the East Coast of the United States. Each wing is shaped like a large rectangle. The lengths of the wings are all adjoining and parallel to each other, forming an even larger rectangle. The occupants of the building participate in full-building evacuations twice a year. On a typical day, the building houses as many as 9000 people.

The building has 14 stairs that exit into building lobbies that then exit to the outside on the ground floor. During the drill, NIST collected data from two of these stairwells. The stairwells were in separate, neighboring wings. The wings observed were mirror images of each other, with the same number of elevators, stairwells, and exterior exit doors. The stairwells in each wing were equally accessible from all rooms and floors. Both stairwells deposited occupants into a lobby through a set of double doors. For Stair A, the stairs were 1440 mm (56.5 in) wide; for Stair B, the stairs were 1540 m (60.5 in) wide. The individual steps measure 200 mm (8 in) rise and 280 mm (11 1/8 in) tread depth in both stairways.

In both stairs, from floors 6 to 2, there are 16 steps between floors (interrupted by a mid-landing 8 step between floors). In Stair A, this same spacing continued down to floor 1. In stair B, there are still 16 steps between floors 2 and 1, but with a mid-landing 10 steps down from floor 2 with an additional 6 steps to floor 1.

A total of 9 camera locations were included in the two stairs observed. In Stair A, cameras were located at the main landings on floors 1, 2, 3, and 5. In Stair B, cameras were located at the main landing on floor 1, and on intermediate landings at floors 1.5, 2.5, 3.5, and 5.5.

The unannounced full-building evacuation drill observed by NIST took place during the summer of 2005 during normal business hours (before lunch). There were 272 participants in the evacuation in the two stairwells (129 in Stair A and 143 in Stair B). During the drill, two groups of three firefighters each travelled up Stair B to floor 5.

Table A-1 shows details of the stair geometry for Building 1.

Table A-1. Stair geometry for building 1, a six-story office building

Stair	**A**	**B**
Total Population using stair (population using exit[a])	129 (126)	143 (108)
Top Floor	6	
Exit Floor	1	
Maximum number of stories traveled	5	
Tread (mm)	280	
Riser (mm)	200	

Floors	6 to 1	
Width mm (and between hand rails, mm)	1440 (1130)	1540 (1230)
Flights (steps)	2 (16)	
Mid-landings	1	
Exit door width (mm)	910	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.2 Building 2

Building 2 is an 11-story educational building located in the Midwest of the United States. The building was equipped with classrooms and a library, as well as office spaces. A corridor encircled the building with offices on the outside of the corridors and classrooms or laboratories on the inside. The building elevators are located on one end of the building with an adjacent corner stairwell. A second stairwell was located diagonally opposite the first stairwell. Classrooms and an assembly space were located on the first three floors of the building.

NIST observed both stairwells. However, all but six of the occupants used the stair nearest to the building elevators. This stair was designated at the South stair and is the only one analyzed for this report. The South stair dimensions varied throughout the stair shaft. The clear width of the stair was 1270 mm (50 in) from floors 11 to 3, and then from floors 3 to 1, the clear width increased to 1680 mm (66 in). The individual steps measure 240 mm (9.5 in) rise and (alternating between) 180 mm and 190 mm (7.25 in and 7.5 in, respectively) tread depth in the South stair.

From floors 11 to 3, there are 2 flights between floors with a mid-landing. Each flight has 10 steps. Then, between floors 3 and 2, there are two flights with a mid-landing with 10 steps down from the 3rd floor to the mid-landing and 11 down from the mid-landing. Between floors 2 and 1,

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[1] In most stairwells, there were occupants observed at one or more camera locations that were not seen exiting the stairwell at the level of exit discharge. In some cases, these were staff with specific building responsibilities, emergency personnel or evacuees who entered at the exit discharge level and did not use the stairs for egress. In others, they were evacuees who chose not to complete the evacuation at some point during their descent down the stairs.

there are 2 flights, with a mid-landing 13 steps down from the 2nd floor and 8 additional steps down from the mid-landing to floor 1.

On the day of the drill, NIST collected data from seven camera locations. Cameras were located at the main landings on floors 1, 2, 4, and 6, and at the mid-landings on floors 2.5, 7.5, and 9.5.

The evacuation drill observed by NIST took place during the fall of 2007 during normal business hours (before lunch). There were 134 participants in the unannounced full building evacuation in one of the two stairwells (128 in the South stair).

Table A-2 shows details of the stair geometry for Building 2.

Table A-2. Stair geometry for building 2, an 11-story education building.

Stair	**S**
Total Population using stair (population using exit[a])	128 (117)
Top Floor	11
Exit Floor	1
Maximum number of stories traveled	10
tread mm	240
riser mm	190

Configuration 1

floors	11 to 3
width mm (and between hand rails, mm)	1270 (965)
flights (steps)	2 (20)
mid-landings	1

Configuration 2

floors	3 to 1
width mm (and between hand rails, mm)	1680 (1370)
flights (steps)	2 (21)
mid-landings	1
Exit door width (mm)	2000

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.3 Building 3

Building 3 is a 13-story office building located on the East Coast of the United States with 11 occupied floors above ground. The occupants of this building perform yearly full-building evacuation drills. On a typical day, the building population is approximately 375 people.

During the drill, evacuation from two stairwells was observed (the East stair and the West stair). The stairwells were equally accessible from all floors in the building. In both stairs, occupants exited from the stairs on the ground floor level (floor 1). The clear width of both stairs was 1120 mm (44 in). The individual steps measure 165 mm (6.5 in) rise and 310 mm (12 1/4 in) tread depth in both stairways.

From floors 13 to 1, there are two flights between floors with a mid-landing. Each flight has 9 steps.

The unannounced evacuation drill observed by NIST took place during the fall of 2005 during normal business hours (before lunch). There were 226 participants in the unannounced full building evacuation in the two stairwells (125 in the East Stair and 101 in the West Stair).

Table A-3 shows details of the stair geometry for Building 3.

Table A-3. Stair geometry for building 3, a 13-story office building.

Stair	**E**	**W**
Total Population using stair (population using exit[a])	125 (116)	101 (84)
Top Floor	13	
Exit Floor	1	
Maximum number of stories traveled	12	
tread mm	310	
riser mm	170	

Configuration 1

floors	13 to 1	
width mm (and between hand rails, mm)	1120 (810)	
flights (steps)	2 (18)	
mid-landings	1	
Exit door width (mm)	910	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.4 Building 4

Building 4 is a 24-story office building. The occupants in this building perform yearly staged evacuation drills; however, they participate in a full-building evacuation drill every five years. On a typical day, the building houses a population of approximately 1500 people.

The building has two stairs; Stairs A and B. Stair A exits onto the 2nd floor lobby where occupants must travel through the lobby to exit the building. Stair B exits directly to the outside on the ground floor (Floor 1). For both stairs, all flights of stairs are 1120 mm wide (44 in) and 1020 mm (40 in) between handrails. Each flight has 10 steps with 180 mm (7 in) high risers and 280 mm (11 in) deep treads.

In Stairs A and B, from floors 24 to 3, there are 2 flights between floors with a mid-landing. In Stair A, between floors 3 and 2 (the exit floor), there are 3 flights with two mid-landings. In Stair B in between floors 3 and 1 (the exit floor), there are 6 flights with five mid landings.

On the day of the drill, NIST collected data from 23 different camera locations in the two stairs observed. In Stair A, 11 cameras were placed on every other floor beginning at the exit floor (Floor 2) and ending with Floor 22. Stair B, 12 cameras were placed every other floor beginning at the exit floor and then continuing on every other even floor from Floor 2 to Floor 22. NIST observed people movement in both Stairs A and B.

The unannounced evacuation drill took place in the spring months of 2008 during normal business hours (before lunch). There were 621 participants in the two monitored stairs in the full building evacuation drill (257 in Stair A and 364 in Stair B). During the drill, three firefighters travelled up Stair A to the 13th floor approximately 1.5 min into the evacuation drill. Also before the drill, firefighters were staged in the stairwells on selected floor landings and began floor searches to ensure that all occupants evacuated as soon as the alarm sounded.

Table A-4 shows details of the stair geometry for Building 4.

Table A-4. Stair geometry for building 4, a 24-story office building.

Stair	**A**	**B**
Total Population using stair (population using exit[a])	257 (246)	364 (321)
Top Floor	22	
Exit Floor	2	1
Maximum number of stories traveled	20	21
tread mm	280	
riser mm	180	

Configuration 1

floors	24 to 3	
width mm (and between hand rails, mm)	1120 (810)	
flights (steps)	2 (20)	
mid-landings	1	

Configuration 2

floors	3 to 2	3 to 1
width mm (and between hand rails, mm)	1120 (810)	
flights (steps)	3 (30)	
mid-landings	2	
Exit door width (mm)	910	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.5 Building 5

Building 5 is a 10-story office building. The occupants in this building practice yearly full-building evacuation drills. On a typical day, the building houses a population of approximately 1000 people.

The building has two stairs; Stairs A and B, both of which exit directly out of the building on the first (or ground) floor. The two stairs are 1270 mm wide (1220 mm between handrails) and the individual steps measure 180 mm (7 in) rise and 280 mm (11 in) tread depth.

In Stairs A and B, from floors 10 to 2, there are 2 flights between floors with a mid-landing. Each flight has 11 steps. From floor 2 to 1 in Stairs A and B, there are also 2 flights with a mid-landing 13 steps down from floor 2 to the mid landing and an additional 14 steps from the mid-landing to the exit floor).

NIST collected data from 10 camera locations in the two stairs observed. In both stairs, cameras were located on main landings beginning with the exit floor (floor 1) and then continuing every other odd numbered floor from floor 3 to floor 9. NIST observed people movement in both Stairs A and B.

The unannounced full building evacuation drill took place in the spring months of 2008 during normal business house (before lunch). There were 807 participants in drill (436 in Stair A and 371 in Stair B). During the drill, six firefighters travelled up Stair B to the 7th floor approximately 8 to 11 minutes into the evacuation drill; i.e., when the drill was almost completed. Also during the drill, firefighters assigned to specific floors began floor searches to ensure that all occupants evacuated as soon as the alarm sounded.

Table A-5 shows details of the stair geometry for Building 5.

Table A-5. Stair geometry for building 5, a 10-story office building.

Stair	**A**	**B**
Total Population using stair (population using exit[a])	436 (384)	371 (350)
Top Floor	10	
Exit Floor	1	
Maximum number of stories traveled	9	
tread mm	280	
riser mm	180	

Configuration 1

floors	10 to 2
width mm (and between hand rails, mm)	1270 (965)
flights (steps)	2 (22)
mid-landings	1

Configuration 2

floors	2 to 1	
width mm (and between hand rails, mm)	1270 (965)	
flights (steps)	2 (27)	
mid-landings	1	
Exit door width (mm)	190	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.6 Building 6

Building 6 is a 62-story office building on the West Coast of the United States. On a typical day, the building houses a population of approximately 2800 people, 2/3 of which are below the 30th floor. The subdivision of office space varies from floor to floor.

The building has four main stairs available for egress (numbered 5, 5-A, 6, and 6-A). Two of the stairs share a common shaft. There are transfer hallways in the buildings that route the egress stairs around mechanical spaces. Occupant movement was observed in four stairs; Stair 5 (which served floors up to floor 52), Stair 5A, and the two stairs that shared a common shaft, Stair 6 and Stair 6A (which served floors up to floor 52). For floors 52 and above, there are only two stairs (stairs 5A and 6). At the time of the drill, there were no occupants above floor 54.

All stairs were 1035 mm (40.75 in) wide and the handrails did not protrude into the stair width. The steps were 200 mm (7 7/8 in) high and 250 mm (10 in) deep. Most floors had 22 steps to the next floor, but the exact configuration varied (the number of intermediary landings varied from one to three). Each of the four stairs had transfer hallways. Stair 5 had transfer hallways on floor

42, at a landing between 42 and 41, floor 22, at a landing between floor 22 and 21, and floor 4. Stair 5A had transfer hallways on floors 42, 22, and 4. Stair 6 had transfer hallways on floors 44, 24, 22, and 4. Stair 6A had transfer hallways on floors 44, 24, 23, 20, and 4.

Data was collected from a total of 42 camera locations in the four stairs. Cameras were placed several floors apart in the four different stairwells. Camera locations are shown below

- Stair 5: Floors 1, 7 13,20,30, 36, 44,51
- Stair 5A: Floors 1, 7, 12, 26, 34, 40
- Stair 6: Floors: 1, 4, 12, 18, 22, 23, 24, 24.5, 28, 34, 40, 46, 51, 54
- Stair 6A: Floors 1, 4, 12, 18, 22, 23, 24, 24.5, 28, 34, 40, 46, 51, 54

The announced drill took place on a 2008 spring morning during regular working hours before lunch. There were a total of 607 participants over the approximately 20 min duration of the voluntary drill.

Table A-6 shows details of the stair geometry for Building 6.

Table A-6. Stair geometry for building 6, a 62-story office building.

Stair	**5**	**5A**	**6**	**6A**
Total population using stair (population using exit[a])	113 (112)	156 (149)	121 (117)	217 (217)
Top floor	52	54		
Exit floor	1			
Maximum number of stories traveled	51	53		
Tread mm	254			
Riser mm	200			

Configuration 1

Floors	52 to 44	54 to 53	54 to 45	54 to 44
Width mm (and between hand rails, mm)	1040 (880)	1070 (910)	1040 (880)	
Flights (steps)	2 (22)			
Mid-landings	1			

Configuration 2

Floors	44 to 43	53 to 44	45 to 44	44 to 43
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	2 (34)	2 (22)	2 (14)	4 (22)
Mid-landings	1			3

Table A-6. continued

Stair	6_5	6_5A	6_6	6_6A

Configuration 3

Floors	43 to 41	44 to 42	44 to 43	43 to 42
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	3 (34)	3 (46)	4 (22)	5 (33)
Mid-landings	2	2	3	4

Configuration 4

Floors	41 to 24	42 to 24	43 to 42	42 to 25
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	2 (22)		5 (33)	2 (22)
Mid-landings	1		4	1

Configuration 5

Floors	24 to 21	24 to 22	42 to 25	25 to 24
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	3 (34)	3 (46)	2 (22)	2 (13)
Mid-landings	2	2	1	1

Configuration 6

Floors	21 to 4	22 to 5	25 to 24	24 to 23
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	2 (22)		2 (13)	4 (22)
Mid-landings	1			3

Configuration 7

Floors	4 to 3	5 to 4	24 to 23	23 to 22
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	5 (33)	4 (22)	4 (22)	3 (24)
Mid-landings	4	3		2

Table A-6. continued

Stair	6_5	6_5A	6_6	6_6A

Configuration 8

Floors	3 to 2	4 to 3	23 to 22	22 to 21
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	6 (36)	5 (39)	3 (24)	4 (22)
Mid-landings	5	4	2	3

Configuration 9

Floors	2 to 1	3 to 2	22 to 21	21 to 20
Width mm (and between hand rails, mm)	1040 (880)	1030 (880)	1040 (880)	
Flights (steps)	5 (37)	6 (36)	4 (22)	2 (22)
Mid-landings	4	5	3	1
Exit door width (mm)	910			

Configuration 10

Floors		2 to 1	21 to 6	20 to 19
Width mm (and between hand rails, mm)		1030 (880)	1040 (880)	
Flights (steps)		5 (31)	2 (22)	2 (22)
Mid-landings		4	1	
Exit door width (mm)		910		

Configuration 11

Floors			6 to 5	19 to 6
Width mm (and between hand rails, mm)			1040 (880)	
Flights (steps)			2 (31)	2 (22)
Mid-landings			1	

Configuration 12

Floors			5 to 4	6 to 5
Width mm (and between hand rails, mm)			1040 (880)	
Flights (steps)			5 (22)	2 (31)
Mid-landings			4	1

Table A-6. continued

Stair	6_6	6_6A
Configuration 13		
Floors	4 to 3	5 to 4
Width mm (and between hand rails, mm)	1040 (880)	
Flights (steps)	3 (24)	5 (22)
Mid-landings	2	4
Configuration 14		
Floors	3 to 2	4 to 3
Width mm (and between hand rails, mm)	1040 (880)	
Flights (steps)	4 (24)	2 (24)
Mid-landings	3	1
Configuration 15		
Floors	2 to 1	3 to 2
Width mm (and between hand rails, mm)	1040 (880)	
Flights (steps)	4 (23)	4 (24)
Mid-landings	3	
Exit door width (mm)	910	
Configuration 16		
Floors		2 to 1
Width mm (and between hand rails, mm)		1040 (880)
Flights (steps)		3 (23)
Mid-landings		2
Exit door width (mm)		910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.7 Building 7

Building 7 is an 18-story office building housed in three wings adjoining a fourth corridor at one end of the wings. The building houses approximately 4000 people and has twelve stairs available for egress, numbered one through twelve. In Building 7's history, there have been small fires and other incidents that initiated the building alarm. Additionally, the building practices fire drills on a yearly basis. Within the year before the observed drill, the local fire department noted one intentional alarm that initiated a building evacuation and one small fire that also initiated a building evacuation without injury to the occupants.

Occupants were observed in four of the 12 stairs; specifically Stairs 1, 3, 7, and 12. These stairs were observed due to their placement in the building – in order to observe stairs from each of the wings in the building. This building is situated on a hill so that the lobby of the building is on the 5th floor and the actual exit for Stair 1 is five floors below on the opposite (downhill) side of the building at ground level (floor 1). Stair 1 exited directly out of the building. Stairs 3, 7, and 12 exited to the lobby area on the fifth floor, each through 910 mm (36 in) wide doors. All four stairs were 1120 mm (44 in) wide and 0.91 m (36 in) between handrails. The individual steps measured 190 mm (7 1/2 in) rise and 250 mm (10 in) tread depth.

In Stair 1 from floors 18 to 4, there are two flights between floors with a mid-landing from floors 18 to 4 and between floor 3 and 2 with 8 steps per flight. From floor 4 to 3 and from floor 2 to 1, there are 9 steps in each flight. In Stairs 3, 7, and 12, there are 2 flights of 8 steps each between floors interrupted by a mid-landing from floors 18 to 6, and then a total of 19 steps in between floors 6 and 5 (9 steps to the mid-landing and then 10 steps to the main landing/exit on floor 5).

On the day of the drill, NIST collected data from 30 different camera locations in the four stairs observed. In Stairs 3, 7, and 12, 7 cameras were placed every other floor beginning at the exit floor (Floor 5) and ending with Floor 17. In Stair 1, 9 cameras were placed every other floor beginning at the exit floor (Floor 1) and ending with Floor 17.

The evacuation drill observed by NIST took place in the spring months of 2008 during normal business hours (before lunch). Within the four stairs observed, there were 1168 participants in the unannounced full building evacuation drill (286 in Stair 1, 312 in Stair 3, 373 in Stair 7, and 197 in Stair 12).

During the drill, a total of 17 firefighters travelled up Stair 12 from the 5th floor to the 12th floor; one group of seven firefighters were followed by another group of ten. Also, the local area Community Emergency Response Team (CERT) members stood at the entrance to Stair 2 and relayed to building occupants that Stair 2 was blocked and they needed to find another stair (likely causing a higher number of occupants to use the stairs near Stair 2 - Stairs 1 and 3 - than normally expected during an evacuation). Last, a person from the CERT team evacuated via Stair 7 assisted by three members of the fire department using an evacuation chair (or stair descent device).

Table A-7 shows details for the stair geometry for Building 7.

Table A-7. Stair geometry for building 7, an 18-story office building

Stair	**1**	**3, 7, 12**
Total population using stair (population using exit[a])	286 (264)	882 (734)[b]
Top floor	17	
Exit floor	1	5
Maximum number of stories traveled	16	12
Tread mm	254	
Riser mm	190	

Configuration 1

Floors	17 to 4	17 to 6
Width mm (and between hand rails, mm)	1120 (810)	
Flights (steps)	2 (16)	
Mid-landings	1	

Configuration 2

Floors	4 to 3	6 to 5
Width mm (and between hand rails, mm)	1120 (810)	
Flights (steps)	2 (18)	2 (19)
Mid-landings	1	
Exit door width (mm)		910

Configuration 3

Floors	3 to 2
Width mm (and between hand rails, mm)	1120 (810)
Flights (steps)	2 (16)
Mid-landings	1

Configuration 4

Floors	2 to 1
Width mm (and between hand rails, mm)	1120 (810)
Flights (steps)	2 (18)
Mid-landings	1
Exit door width (mm)	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

b – total for all three stairwells. Individually, 312 (291), 373 (262), and 197 (181) for stairs 7_3, 7_7, and 7_12, respectively

A.8 Building 8

Building 8 is a 30-story office building on the East Coast of the United States (although the floors above ground are numbered up to 31; i.e., without a floor numbered as the 13th floor). On a typical day, the building houses a population of approximately 2100 people.

The building has two stairs (North and South, designated N and S here) that both exit on the 2nd floor onto the street level. The two stairs are 1380 mm (10 3/4 in) wide (1260 mm (42 1/4 in) between handrails) and the individual steps measure 180 mm rise and 270 mm tread depth.

From floors 31 to 4, there are 2 flights between floors with a mid-landing. Between floors 3 and 4, the stair configuration introduces a horizontal transfer corridor around the mechanical area. The corridors included three bends and the width of each section varied. From floors 3 to 2, there are 27 steps (interrupted by two mid landings with 9 steps between each landing). There are 9 steps per flight on all flights of both stairs except the flight leading to the transfer hallway in both stairs where there are 7 steps from the 4th floor down to the transfer hallway. Finally, there is a horizontal travel distance from the North stair to the exit of the building.

On the day of the drill, NIST collected data from 30 different camera locations in the two stairs observed. In both stairs, the cameras were placed on every other floor which meant the even-numbered floors from floors 30 to 14 (every other floor), and the odd-numbered floors from 11 to 5. Cameras were also placed on even floors at the base of the stair (Floors 2 and 4) since Floor 2 was the exit level.

The evacuation drill observed by NIST took place in the fall months of 2008 during normal business hours (before lunch). The full-scale, simultaneous building evacuation was unannounced; meaning that the population was made aware of the evacuation drill only by the sound of the fire alarm. Additionally, the elevators were not available for the population to use during the drill. Only people with disabilities were able to use the elevators for evacuation, and only the freight elevator was available for their use. Overall, there were 1218 participants in this evacuation drill (685 in the North Stair and 533 in the South stair).

Table A-8 shows details for the stair geometry for Building 8.

Table A-8. Stair geometry for building 8, a 31-story office building.

<table>
<tr><th>Stair</th><th>N</th><th>S</th></tr>
<tr><td>Total population using stair (population using exit[a])</td><td>685 (676)</td><td>533 (483)</td></tr>
<tr><td>Top floor</td><td colspan="2">30</td></tr>
<tr><td>Exit floor</td><td colspan="2">2</td></tr>
<tr><td>Maximum number of stories traveled</td><td colspan="2">28</td></tr>
<tr><td>Tread mm</td><td colspan="2">270</td></tr>
<tr><td>Riser mm</td><td colspan="2">180</td></tr>
</table>

Configuration 1

<table>
<tr><td>Floors</td><td colspan="2">29 to 4</td></tr>
<tr><td>Width mm (and between hand rails, mm)</td><td colspan="2">1380 (1070)</td></tr>
<tr><td>Flights (steps)</td><td colspan="2">2 (18)</td></tr>
<tr><td>Mid-landings</td><td colspan="2">1</td></tr>
</table>

Configuration 2

<table>
<tr><td>Floors</td><td colspan="2">4 to 3</td></tr>
<tr><td>Width mm (and between hand rails, mm)</td><td colspan="2">1380 (1070)</td></tr>
<tr><td>Flights (steps)</td><td>2 (16)</td><td>4 (32)</td></tr>
<tr><td>Mid-landings</td><td>1</td><td>3</td></tr>
</table>

Configuration 3

<table>
<tr><td>Floors</td><td colspan="2">3 to 2</td></tr>
<tr><td>Width mm (and between hand rails, mm)</td><td colspan="2">1380 (1070)</td></tr>
<tr><td>Flights (steps)</td><td colspan="2">3 (27)</td></tr>
<tr><td>Mid-landings</td><td colspan="2">2</td></tr>
<tr><td>Exit door width (mm)</td><td>910</td><td>910</td></tr>
</table>

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.9 Building 9

Building 9 is a 13-story residential building that contains 175 living units. The building is designated for older adults with a typical population of approximately 200 residents.

The building has two stairs, Stairs 1 and 2, both of which exit directly out of the building on ground floor. The two stairs are 1370 mm (54 in) wide, 1350 mm (53 in) between handrails,

In Stairs 1 and 2, from floors 12 to 1, there are 2 flights between floors with a mid-landing. From floor 1 to the ground floor in Stairs 1 and 2, there are 3 flights between floors with two mid-landings. Each flight has 9 steps measuring 150 mm (6 in) rise and 320 mm (12.6 in) tread depth.

On the day of the drill, NIST collected data from 14 different camera locations in the two stairs. Cameras were placed on the ground (exit) floor and on floors 1, 3, 5, 7, 9, and 11 in both stairs.

The announced, mandatory evacuation drill took place in the fall of 2009 in the morning (before noon). Building management made a decision to announce this evacuation drill so that building occupants would not be upset by the drill and instead, ready and prepared to take part. The evacuation scenario used for the drill was a gas leak near the building, which rendered the elevators inoperable for egress.

The drill lasted for 75 min; however, video cameras were only able to capture 56 min of the evacuation. In the 13-story building 71 people evacuated in Stair 1 and 56 people in Stair 2. These numbers include all evacuees of the building and building staff that were either evacuating themselves or assisting residents; however these numbers do not include firefighters assisting evacuees.

Throughout the drill, firefighters from various local fire stations arrived on scene and assisted building occupants down the stairs. Firefighters did interact briefly with evacuating occupants inside the stairs; however, when this would occur, the evacuating occupants were given priority (i.e., firefighters would step aside and allow evacuating occupants to pass by). Building occupants evacuated via the stairs on their own, with some assistance from firefighters or other occupants, or via evacuation chairs guided by firefighters[2]. A total of 45 firefighters from 8 different companies and additional support personnel were deployed for this evacuation drill and used this drill as a training opportunity on how to evacuate occupants with mobility impairments using one type of evacuation chair. Staff members assisted some occupants; however, firefighters assisted evacuees in evacuation chairs.

Table A-9 shows details for the stair geometry for Building 9.

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[2] Evacuation chairs were used to assist individuals with mobility impairments down the stairs. The chairs were escorted by two to three firefighters at any one time. The type of evacuation chair used was one in which the individual sits upright on landings, and is tilted slightly back on stairs so that the chair may slide on the diagonal of the steps with ease. The specifics about chair manufacturer are not discussed in this paper.

Table A-9. Stair geometry for building 9, a 13-story residential building.

Stair	**A**	**B**
Total Population using stair (population using exit[a])	71 (69)	56 (56)
Top Floor	12	
Exit Floor	0	
Maximum number of stories traveled	12	
tread mm	320	
riser mm	150	

Configuration 1

floors	12 to 1
width mm (and between hand rails, mm)	1370 (1070)
flights (steps)	2 (18)
mid-landings	1

Configuration 2

floors	1 to 0	
width mm (and between hand rails, mm)	1370 (1070)	
flights (steps)	3 (27)	
mid-landings	2	
Exit door width (mm)	910	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.10 Building 10

Building 10 is a six-story residential building containing 133 living units. The building is designated as an assisted living facility for older adults.

Occupants evacuated in one of the three stairwells that exit to the ground floor. Due to technical difficulties, only two out of the three could be monitored (Stairwell 2 and Stairwell 3). However, the majority of the residents evacuated through the stairwell 2 during the drill. The two stairwells have similar dimensions, being 1120 mm (44 in) wide, with an effective width of 950 mm (37 1/2 in). The individual steps measure 170 mm (6 1/2 in) rise and 300 mm (12 in) tread depth. The first floors of Stairwell 2 and Stairwell 3 have 18 steps total; Stairwell 2 has 9 steps before and after a mid-landing, while Stairwell 3 has 10 and then 8 steps after a mid-landing. Floors 2 to 6 of both stairwells have 18 steps between floors, interrupted by mid-landings after a flight of 9 steps.

On the day of the drill, NIST collected data from 12 different cameras locations, with cameras placed on every floor of Stairwell 2 and Stairwell 3.

The building evacuation drill began around 10 am in the Fall of 2010. Firefighters and staff members knocked on the doors of residents who volunteered to initiate the evacuation. Building management decided to announce this drill and not sound off the alarm so that older occupants who did not volunteer would remain calm. The exercise scenario was flooding in the basement from a water main break. In the scenario, water filled the elevator pits and approached the main mechanical room, thus rendering the elevators inoperable. If the flood persisted, the water would reach the electric panels and require all power to be shut down. Therefore, management chose to evacuate residents from the building by stairwells. The video cameras captured 50 min of the evacuation, which was cut short due to time constraints of the training exercise (i.e., not all residents evacuated the building). Throughout the drill, firefighters from different companies as well as support personnel arrived on scene to help building occupants travel down the stairs. Residents evacuated via the stairwells on their own, with a cane, with assistance from firefighters or other occupants, or by stair descent devices. The firefighters used this drill as a training opportunity for evacuating mobility-impaired individuals on stair descent devices.

In the six-story building, 47 residents were evacuated, with 45 in Stairwell 2 and 2 in Stairwell 3. The reason for the difference in stair usage was because the firefighters designated Stairwell 2 as their main evacuation stairwell, using it almost exclusively for evacuation, while the other two stairwells were used to carry vacant evacuation chairs back up to waiting residents. In Stairwell 2, two occupants on stair chairs were transferred from Stairwell 2 to Stairwell 3 because of slight congestion. These numbers do not include firefighters assisting evacuees.

Table A-10 shows details for the stair geometry for Building 10.

Table A-10. Stair geometry for building 10, a six-story residential assisted-living facility.

Stair	**2**	**3**
Total population using stair (population using exit[a])	45 (45)	2 (---)
Top floor	6	
Exit floor	1	
Maximum number of stories traveled	5	
Tread mm	305	
Riser mm	165	

Configuration 1

Floors	6 to 1	
Width mm (and between hand rails, mm)	1120 (950)	
Flights (steps)	2 (18)	
Mid-landings	1	
Exit door width (mm)	910	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.11 Building 11

Building 11 is a 22-story office (courthouse) building on the West Coast of the United States. On a typical day, the building houses a population of approximately 600 people.

This building has 22 stories, 19 of which are occupied, and has four stairways for evacuation. Two exit stairs, Stairs 1 and 2 are public stairs that provide access from floor 18 (Stair 2) or 19 (Stair 3) to the exit (either the lobby or the basement floor exit). The other two exit stairs, Stairs 3 and 4, are secured stairs. Stair 3 provides access to all occupied floors. Stair 4 services floors 7 to 1. During the evacuation, NIST set up video cameras in two of the four exit stairs, specifically Stairs 2 and 3, to capture people movement on exit stairways and through stair/exit doors. Stair 2 is 1270 mm (50 in) wide (1170 m [46 in] between handrails) and Stair 3 is 1180 mm (46 1/2 in) wide (1070 mm [42 in] between handrails). In Stair 2, the individual steps measure 180 mm (7 in) rise and 280 mm (11 in) tread depth, and in Stair 3, the individual steps measure 160 mm (6 1/2 in) rise and 300 mm (12 in) tread depth.

There were differences in levels of exit discharge – occupants should exit Stair 2 at the lobby level (floor 2), whereas occupants should exit Stair 3 at the ground level (floor 1).

In Stair 2, from floors 18 to 7, there are 18 steps between floors interrupted by a mid-landing after 9 steps. From floors 7 to 2, in Stair 2, there are 24 steps between floors interrupted by a mid-landing after 12 steps. In Stair 3, from floors 19 to 7, there are 18 steps between floors interrupted by a mid-landing after 9 steps. From floors 7 to 2, in Stair 3, there are 24 steps between floors interrupted by a mid-landing after 12 steps. Finally, from floor 2 to 1, there are 25 steps total (5 steps from floor 2 to the first mid landing, 12 steps to another mid landing, and then 8 steps to the exit location on floor 1).

Data was collected from 19 different camera locations in the two stairs observed. In Stair 2, cameras were placed on every even floor started with floor 18 to floor 2 (for a total of 9 cameras), and in Stair 3, cameras were placed on every odd floor beginning at floor 19 and ending at floor 1 (for a total of 10 cameras).

The evacuation drill took place in the fall months of 2010 during normal business house (before lunch). There were 224 participants in the unannounced full building evacuation drill (135 in Stair 2 and 89 in Stair 3). During the drill, an individual from the 11th floor was evacuated via a stair descent device in Stair 3.

Table A-11 shows details for the stair geometry for Building 11.

Table A-11. Stair geometry for building 11, a 22-story office building.

Stair	**2**	**3**
Total population using stair (population using exit[a])	135 (77)	89 (83)
Top floor	18	19
Exit floor	1	
Maximum number of stories traveled	17	18
Tread mm	280	
Riser mm	180	

Configuration 1

Floors	18 to 7	19 to 7
Width mm (and between hand rails, mm)	1270 (1170)	1180 (1070)
Flights (steps)	4 (36)	
Mid-landings	3	

Configuration 2

Floors	7 to 2	
Width mm (and between hand rails, mm)	1270 (1170)	1180 (1070)
Flights (steps)	2 (24)	
Mid-landings	1	
Exit door width (mm)	910	

Configuration 3

Floors		2 to 1
Width mm (and between hand rails, mm)		1180 (1070)
Flights (steps)		3 (25)
Mid-landings		2
Exit door width (mm)		910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.12 Building 12

Building 12 is a 6-story office building located in the East Coast of the United States.

The building has two sinistral stairs (individuals descend in a clockwise direction), Stair A and Stair B. Both stairs serve all six floors of the building and exit at the first floor. Both stairs are 1120 mm (44 in wide) and 1040 mm (41 in) between handrails. Individual steps measure 180 mm (7 in) rise and 290 mm (11 1/2 in) tread depth.

In Stairs A and B, from floors 6 to 2, there are two flights between floors with a mid-landing. Each flight has 10 steps. In Stair A, between floor 2 and 1 (the exit floor), there are 3 flights with two mid-landings. From floor 2, there are 10 and 13 steps to the mid-landings and finally 12 steps down to floor 1. In Stair B, between floor 2 and 1 (the exit floor), there are 3 flights with two mid-landings. From floor 2, there are 6 and 10 steps to the mid-landings and finally 16 steps down to floor 1.

On the day of the drill, cameras were placed at every floor of both stairwells to capture a view of each floor's main landings. The camera also recorded the time in which people moved through the space (i.e. when people enter and exit landings). NIST observed people movement in both stairs.

The unannounced full-building evacuation drill took place in the spring of 2011 during normal business hours (before lunch). There were 76 participants in the two monitored stairs during the evacuation (64 in Stair A and 12 in Stair B).

Table A-11 shows details for the stair geometry for Building 12.

Table A-12. Stair geometry for building 12, a six-story office building.

Stair	**A**	**B**
Total population using stair (population using exit[a])	64 (61)	12 (12)
Top floor	6	
Exit floor	1	
Maximum number of stories traveled	5	
Tread mm	290	
Riser mm	180	

Configuration 1

Floors	6 to 2
Width mm (and between hand rails, mm)	1120 (1040)
Flights (steps)	2 (20)
Mid-landings	1

Configuration 2

Floors	2 to 1	
Width mm (and between hand rails, mm)	1120 (1040)	
Flights (steps)	3 (35)	3 (32)
Mid-landings	2	2
Exit door width (mm)	910	910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

A.13 Building 13

Building 13 is a 15-story residential high-rise building that contains 203 living units as well as a commercial space on the T1 level of the building. The building actually has floors above ground from 1 to 16 because it does not contain a 13th floor.

The building has two stairs, Stairs 1 and 2. Stair 1 ends at the T1 level (one level underground in reference to the building's front entrance) and Stair 2 ends at the T2 level (two levels underground in reference to the building's front entrance). The building was built on a hill that allowed for three separate exits levels. The two stairs are 1120 mm (44 in) wide, 980 mm (38 5/8 in) between handrails, and the individual steps measure 170 mm (6 1/2 in) rise and 300 mm (12 in) tread depth.

In Stairs 1 and 2, from floors 16 to 15, there are 9 steps to the mid landing, and then another 8 steps to floor 15. Between floors 15 and 1, there are 16 steps between floors (interrupted by a mid-landing 8 steps between floors). From floor 1 to the T1 level, there are 9 steps to the mid landing, and then another 12 steps to the T1 floor (where occupants would exit Stair 1. In Stair 2, from the T1 level to the T2 level, there are 10 steps to the mid landing, and then another 6 steps to the T2 level, where occupants in Stair 2 would exit.

On the day of the drill, NIST collected data from 18 different camera locations in the two stairs. In Stair 2, cameras were located at level T1 (one floor underground; the exit level), every other floor from floor 1 up to floor 9, and floors 10, 12, and 15. In Stair 2, cameras were located on floor T2 (two level underground, the exit level), floor 1, and every other floor from floor 2 to 15.

The announced, voluntary evacuation drill took place in the spring of 2011 in the morning (before noon). Building management made a decision to announce this evacuation drill so that building occupants would not be upset by the drill and instead, ready and prepared to take part. The evacuation scenario used for the drill was a fire scenario in the building which would require a full building evacuation. When the fire alarm sounded, most building occupants evacuated via the stairs on their own. The fire department was also present for the evacuation drill, and evacuated one occupant using an evacuation chair.

In the 16-story building, 36 people evacuated in Stair 1 and 39 people in Stair 2 without assistance. Additionally firefighters assisted one additional occupant in an evacuation chair in Stair 1; these numbers do not include firefighters assisting evacuees.

Table A-13 shows details for the stair geometry for Building 13.

Table A-13. Stair geometry for building 13, a 15-story residential building.

Stair	**1**	**2**
Total population using stair (population using exit[a])	36+1[b] (35+1)	39 (39)
Top floor	15	
Exit floor	T1	T2
Maximum number of stories traveled	15	16
Tread mm	300	
Riser mm	170	

Configuration 1

Floors	15 to 1	15 to 1
Width mm (and between hand rails, mm)	1120 (980)	
Flights (steps)	2 (16)	
Mid-landings	1	

Configuration 2

Floors	1 to T1	1 to T1
Width mm (and between hand rails, mm)	1120 (980)	
Flights (steps)	2 (21)	
Mid-landings	1	
Exit door width (mm)	910	

Configuration 3

Floors		T1 to T2
Width mm (and between hand rails, mm)		1120 (980)
Flights (steps)		2 (16)
Mid-landings		1
Exit door width (mm)		910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

b – firefighters assisted one additional occupant in an evacuation chair in Stair 1

A.14 Building 14

Building 14 is a 21-story office (courthouse) building in the Midwest of the United States. On a typical day, the building houses a population of approximately 600 people.

This building has 21 stories above ground and has three main stairways for evacuation. Two exit stairs, Stairs 1 and 2 are public stairs that provide access from floor 21 to the exit (either the lobby or the lower level 3 floor exits since Stair 2 exits on the rear of the building, three floors below the grade in the front of the building). The third exit stair, Stair 3, is secured. Stair 3 provides access to all floors. Additional stairs in the building include a number of convenience stairs that connect adjacent floors but do not travel the full height of the building and stairs used for egress of below grade levels (stairwells 4 and 5). NIST collected data from Stairs 1 and 2. Stair 1 is 1060 mm (41 3/4 in) wide and 920 mm (36.3 in) between handrails. Stair 2 is 1040 mm (40 ¾ in) wide and 900 mm (35 3/8 in) between handrails. Individual stairs measure 170 mm (6 7/8 in) rise and 300 mm (11.9 in) tread depth. There were differences among the exit stairs' levels of exit discharge – occupants exit Stair 1 at ground level in the rear of the building (floor T3) and exit Stair 2 at the lobby level (floor 1) in the front of the building.

Both stairs have a unique triangular configuration for the above-ground floors. Table A-14 and Appendix A show details for the stair geometry. From floors 21 to 7, there are 6 flights of stairs with five mid-landings, different numbers of steps per flight, and additional horizontal travel distances to maintain the triangular shape of the stairs. From Floors 7 down to 2, there are 3 flights with two mid-landings. For Stair 1 from floor 2 down to the exit on T3, there are 6, 3, 4, and 5 flights respectively (with 5, 2, 3, and 4 mid-landings).

On the day of the drill, NIST collected data from 23 different camera locations in the two stairwells. In Stair 1, 12 cameras were placed on every other floor from T3 up to 20. In Stair 2, cameras were placed on floor 1 (the exit floor) and every other floor from floor 2 up to 20.

The unannounced evacuation drill took place in the fall of 2011 during normal business hours (before lunch). There were 305 participants in the two monitored stairs (175 in Stair 1 and 130 in Stair 2).

Table A-13 shows details for the stair geometry for Building 14.

Table A-14. Stair geometry for building 14, a 21-story office building.

Stair	**1**	**2**
Total population using stair (population using exit[a])	175 (157)	130 (100)
Top floor	21	21
Exit floor	L3	1
Maximum number of stories traveled	24	20
Tread mm	300	
Riser mm	170	

Configuration 1

Floors	21 to 20	21 to 20
Width mm (and between hand rails, mm)	1060 (920)	1040 (900)
Flights (steps)	3 (22)	3 (22)
Mid-landings	2	2

Table A-14, continued

Stair	14_1	14_2

Configuration 2

Floors	20 to 8	20 to 8
Width mm (and between hand rails, mm)	1060 (920)	1040 (900)
Flights (steps)	6 (32)	6 (32)
Mid-landings	5	5

Configuration 3

Floors	8 to 7	8 to 7
Width mm (and between hand rails, mm)	1060 (920)	1040 (900)
Flights (steps)	6 (40)	6 (40)
Mid-landings	5	5

Configuration 4

Floors	7 to 6	7 to 2
Width mm (and between hand rails, mm)	1060 (920)	1040 (900)
Flights (steps)	3 (23)	3 (23)
Mid-landings	2	2

Configuration 5

Floors	6 to 5	2 to 1
Width mm (and between hand rails, mm)	1060 (920)	1040 (900)
Flights (steps)	3 (22)	2 (32)
Mid-landings	2	1
Exit door width (mm)		910

Configuration 6

Floors	5 to 3	
Width mm (and between hand rails, mm)	1060 (920)	
Flights (steps)	3 (23)	
Mid-landings	2	

Configuration 7

Floors	3 to 2	
Width mm (and between hand rails, mm)	1060 (920)	
Flights (steps)	3 (22)	
Mid-landings	2	

Table A-14, continued

Stair	14_1	14_2

Configuration 8

Floors	2 to 1	
Width mm (and between hand rails, mm)	1060 (920)	
Flights (steps)	6 (32)	
Mid-landings	5	

Configuration 9

Floors	1 to T1	
Width mm (and between hand rails, mm)	1060 (920)	
Flights (steps)	3 (32)	
Mid-landings	2	

Configuration 10

Floors	T1 to T2	
Width mm (and between hand rails, mm)	1060 (920)	
Flights (steps)	4 (32)	
Mid-landings	3	

Configuration 11

Floors	T2 to T3	
Width mm (and between hand rails, mm)	1060 (920)	
Flights (steps)	5 (31)	
Mid-landings	4	
Exit door width (mm)		910

a – number of evacuees that were observed at the camera location at the exit from the stairwell[1]

B. Averaging Movement Speeds

This appendix details the use of the harmonic mean as well as its calculation and its associated uncertainties. Overall movement speed for each occupant, discussed in section 4.14, was determined from the total travel distance (from where he/she entered the stairwell to the exit at the bottom of the stairwell) divided by the difference between entry and exit times.

To begin, consider an occupant that travels three consecutive 10 m sections in 10 s, 15 s, and 20 s (thus with local speeds of 1.00 m/s, 0.67 m/s, and 0.5 m/s, respectively). The arithmetic mean of the three local speeds is 0.72 m/s. However, the overall mean speed considering the total distance and time travelled is 30 m / 45 s or 0.67 m/s, which is the harmonic mean of the local speeds. This, correct, mean speed uses the harmonic mean.

To see this in detail, we begin with the definition of the weighted harmonic mean,

$$H = \frac{\sum_{i=1}^{n} w_i}{\sum_{i=1}^{n} w_i / x_i} \tag{1}$$

where H is the harmonic mean, and w_i is the weight of the value x_i in the average. Suppose person *A* travels along a path, *P*, broken into *n* segments of lengths $d_1, d_2, \ldots, d_n$ traveling the segments at speeds $v_1, v_2, \ldots, v_n$. The overall average speed, v_a, of *A* along the path is simply the total path length divided by the total time to traverse the path, so the overall average speed of person *A* is

$$v_a = \frac{d_1 + d_2 + \ldots + d_n}{t_1 + t_2 + \ldots + t_n} \tag{2}$$

where t_i is the time taken to traverse the i^{th} segment. By definition, $t_i = d_i / v_i$, which can be substituted into Eq (2) so that the overall average speed of *A* is

$$v_a = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_i} \tag{3}$$

which is the weighted harmonic mean of v_i, with weights d_i. Therefore the harmonic mean of an occupant's local speeds is equal to that occupant's overall average speed. Since the arithmetic mean of positive values is always greater than the harmonic mean the arithmetic mean of the local speeds would be larger than the overall average speed of the occupant.

Now consider the average of n occupants traveling through a section with length d with travel times t_i. If v_{pop} is the average speed for the population than d/v_{pop} should equal to the average time the occupants spend in the section as shown here

$$\begin{gathered} \frac{d}{v_{pop}} = \frac{1}{n}\sum_{i=1}^{n} t_i \\ \frac{nd}{\sum_{i=1}^{n} t_i} = v_{pop} \end{gathered} \tag{4}$$

which has the same form as Eq (2) and is the harmonic mean of the individual speeds where all $w_i = d$.

The same idea can be used to define the overall average speed for a population on a stair. In this case we will define the overall average speed for the population as the value v_{pop} such that the average distanced traveled by the occupants divide by v_{pop} will equal the average time the occupants are in the stair. Mathematically that looks like

$$\begin{gathered} \frac{1}{n}\sum_{i=1}^{n} d_i \bigg/ v_{pop} = \frac{1}{n}\sum_{i=1}^{n} t_i \\ v_{pop} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} t_i} \end{gathered} \tag{5}$$

where d_i and t_i are the distance and the travel time for the i^{th} occupant respectively and (5) is again the weighted harmonic mean of the average speeds of the occupants.

From v_{pop} for a section, it is clear the weightings are the distance a speed is averaged over. To calculate the overall average speed from the local average speeds of each section we just use the same calculation. Assume the stair has m sections, than

$$w_j = n_j d_j \tag{6}$$

where w_j, n_j, and d_j are the weighting for, the number of occupants passing through, and the distance of the j^{th} section. Substituting into (1) gives

$$v_{pop} = \frac{\sum_{j=1}^{m} n_j d_j}{\sum_{j=1}^{m} \frac{n_j d_j}{v_{\mathrm{pop},j}}} \tag{7}$$

where v_{pop} is the average speed of the population in the stair and $v_{pop,j}$ is the harmonic mean of the speeds in the j^{th} section.

We can extend this definition of the average speed of the population in a stair to the average speed of the population for a building or for the total population in all the evacuations.

B.1 Uncertainty Analysis of Averages

We can rewrite (2) as

$$v_a = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_i}} = \frac{1}{\sum_{i=1}^{n} \left(\frac{1}{v_i}\right) \frac{d_i}{\sum_{i=1}^{n} d_i}} = \frac{1}{H} \tag{8}$$

where H is the weighted mean of $\left(1/v_i \right), i = 1, \ldots, n$.

Therefore, $v_a = f(H)$, where $f(u) = 1/u$ and $f'(u) = -1/u^2$. Here the propagation of errors formula may be applied. Using a first-order Taylor series expansion about $\mu_H = E[H]$, the mean of *H*,

$$\begin{aligned} Var\left[f(H)\right] &\approx f'(\mu_H)^2 \sigma_H^2 \\ &= \frac{\sigma_H^2}{\mu_H^4} \end{aligned} \tag{9}$$

where $\sigma_H^2 = Var[H]$, the variance of H. So,

$$Var\left[v_a\right] \approx \frac{\sigma_H^2}{\mu_H^4} \tag{10}$$

Assuming $v_1, v_2, \ldots, v_n$ are independent and identically distributed,

$$\begin{aligned} \mu_H &= E[H] = E\left[\sum_{i=1}^{n} \left(\frac{1}{v_i}\right) \frac{d_i}{\sum_{i=1}^{n} d_i}\right] = E\left[\frac{1}{v_1}\right] \\ \sigma_H^2 &= Var[H] = Var\left[\frac{1}{v_1}\right] \sum_{i=1} \frac{d_i^2}{\left(\sum_{i=1}^{n} d_i\right)^2} \end{aligned} \tag{11}$$

Since v_i are identically distributed, $E\left[1/v_1\right] = E\left[1/v_2\right] = \ldots = E\left[1/v_n\right]$ and $Var\left[1/v_1\right] = Var\left[1/v_2\right] = \ldots = Var\left[1/v_n\right]$ so that in the above formula v_1 is used to indicate the average value and variance of the inverse of the speed for an individual as opposed to the series or sum or some other combination of the population.

Using the sample moments, both μ_H and σ_H^2 may be estimated

$$\hat{\mu}_H = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{v_i}$$
$$\hat{\sigma}_H^2 = \frac{1}{n-1}\sum\left(\frac{1}{v_i} - \hat{\mu}_H\right)^2 \times \sum_{i=1}^{n}\frac{d_i^2}{\left(\sum_{i=1}^{n} d_i\right)^2} \tag{12}$$

B.2 Sample Variation from the Harmonic Mean

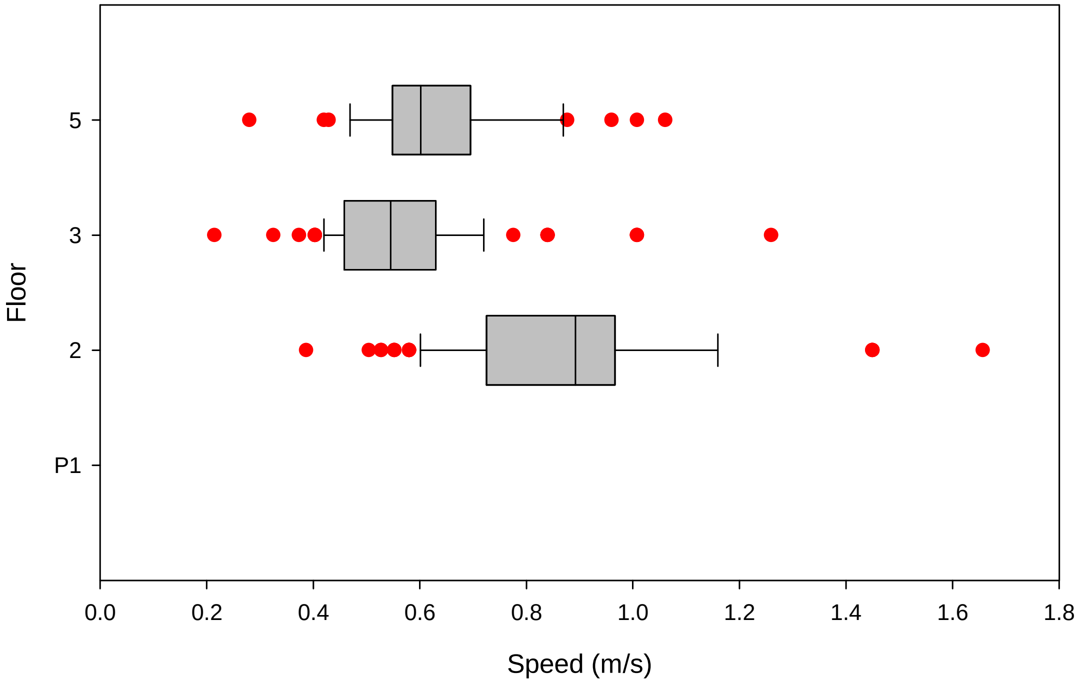
The sample variation measures the average variation from the arithmetic mean. Since we are using the harmonic mean as the 1st order statistic for speed it is natural to consider the deviation of individual average speeds from the harmonic average speed, v_a. This gives almost the normal sample variation formula

$$\sigma_{v_i}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(v_i - v_a\right)^2 \tag{13}$$

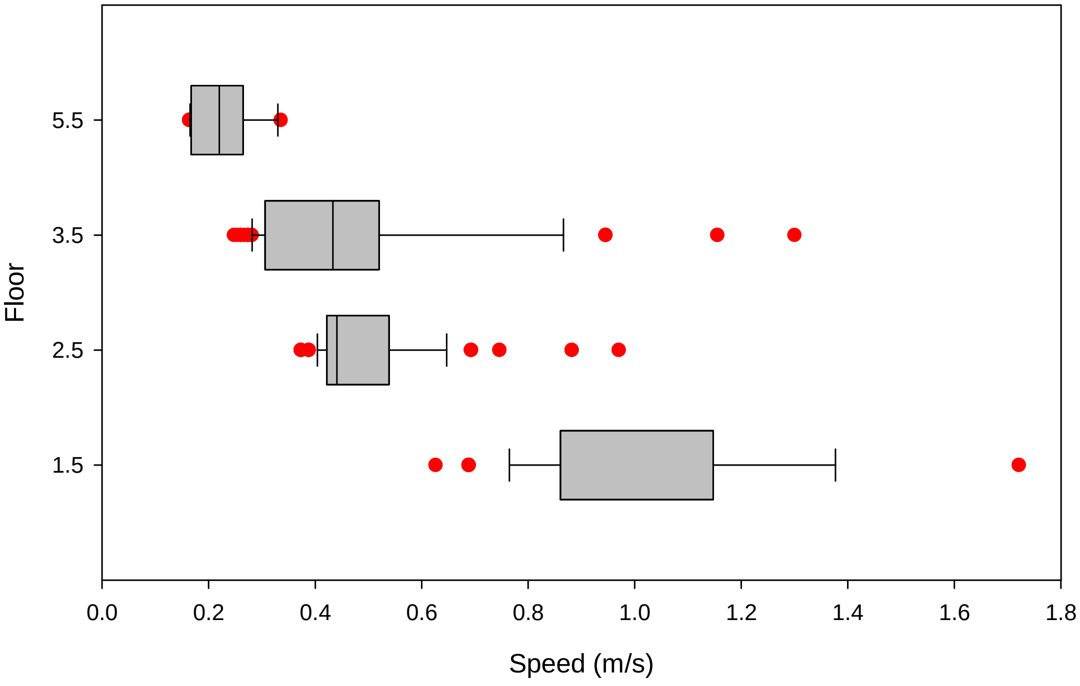
where $\sigma_{v_i}^2$ is the variation of individual speeds using the harmonic mean speed rather than the more typical arithmetic mean for consistency with the average speed calculation.

C. Local Travel Speeds

This appendix includes box plots of the local speed in the 30 stairs. Included in the study. In addition to the median, interquartile range, and 95 % confidence intervals, the graphs also include all the outliers (those values outside the 95 % confidence intervals) for each camera location. It is intended to show the variability of the local movement speeds.

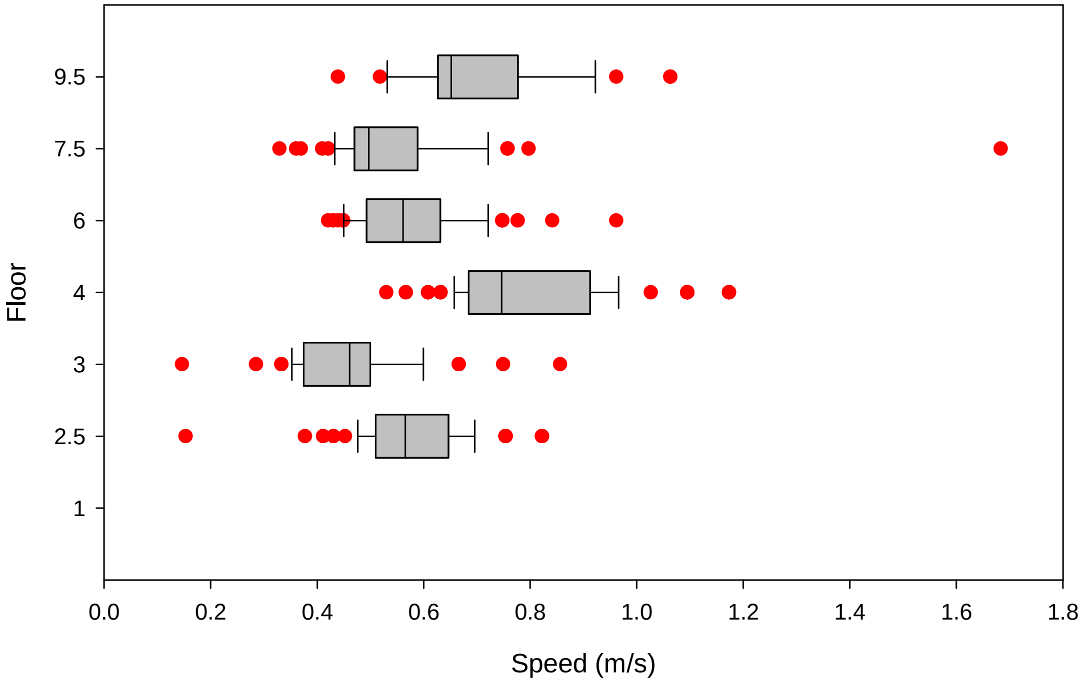


Stair 1 A



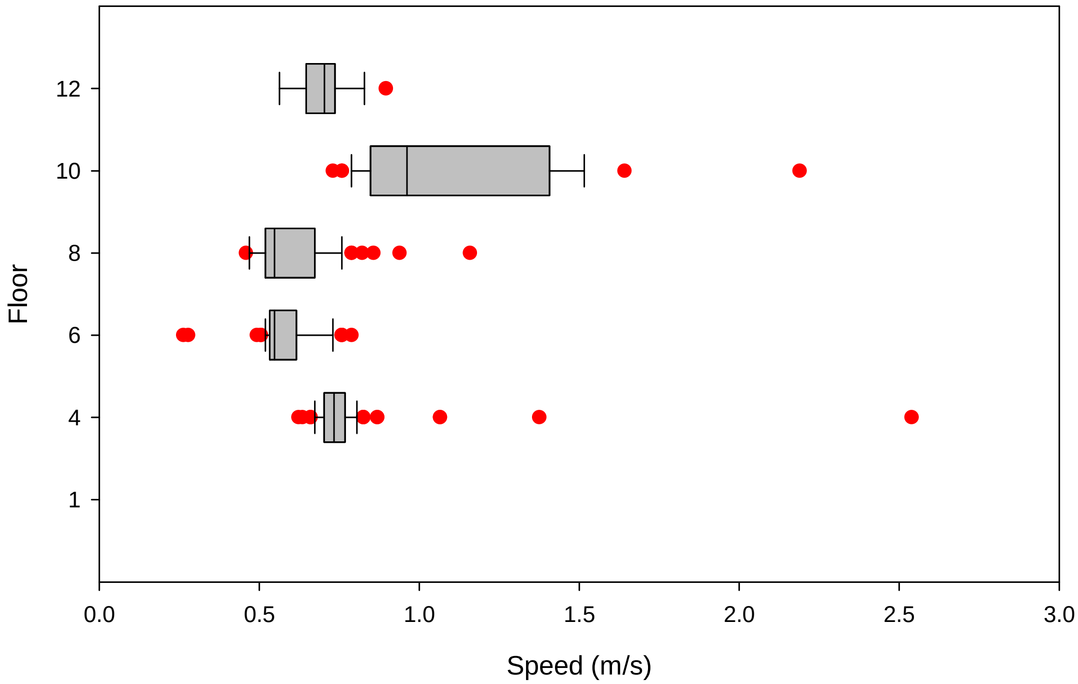
Stair 1 B

Figure C-1. Local Movement Speeds for All Camera Locations in Building 1

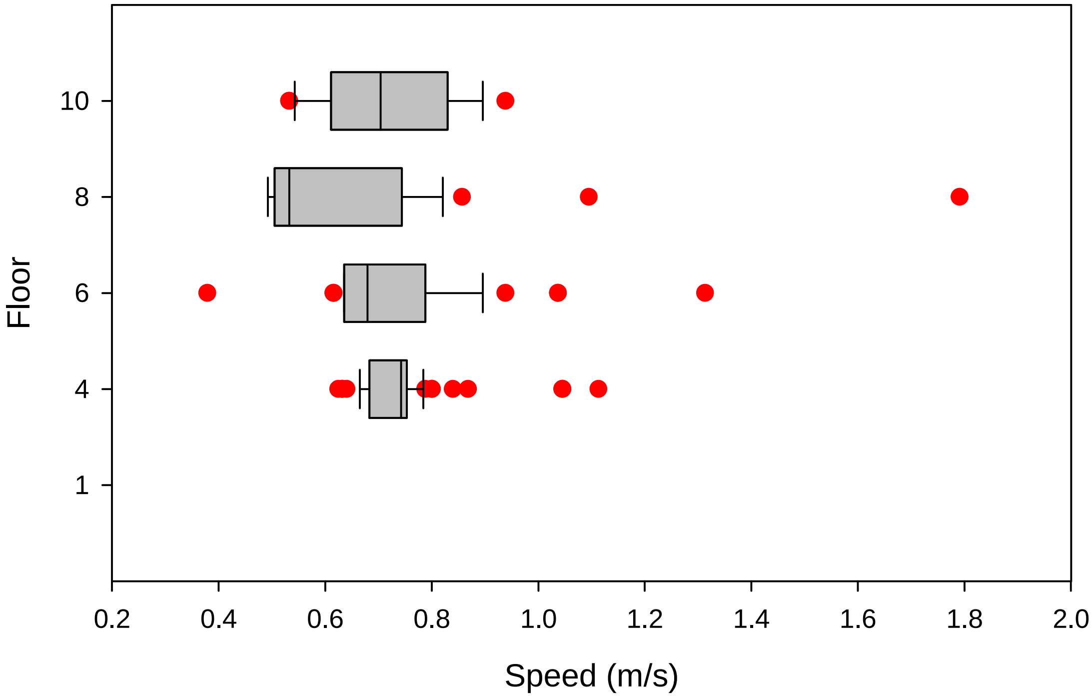


Stair 2 S

Figure C-2. Local Movement Speeds for All Camera Locations in Building 2

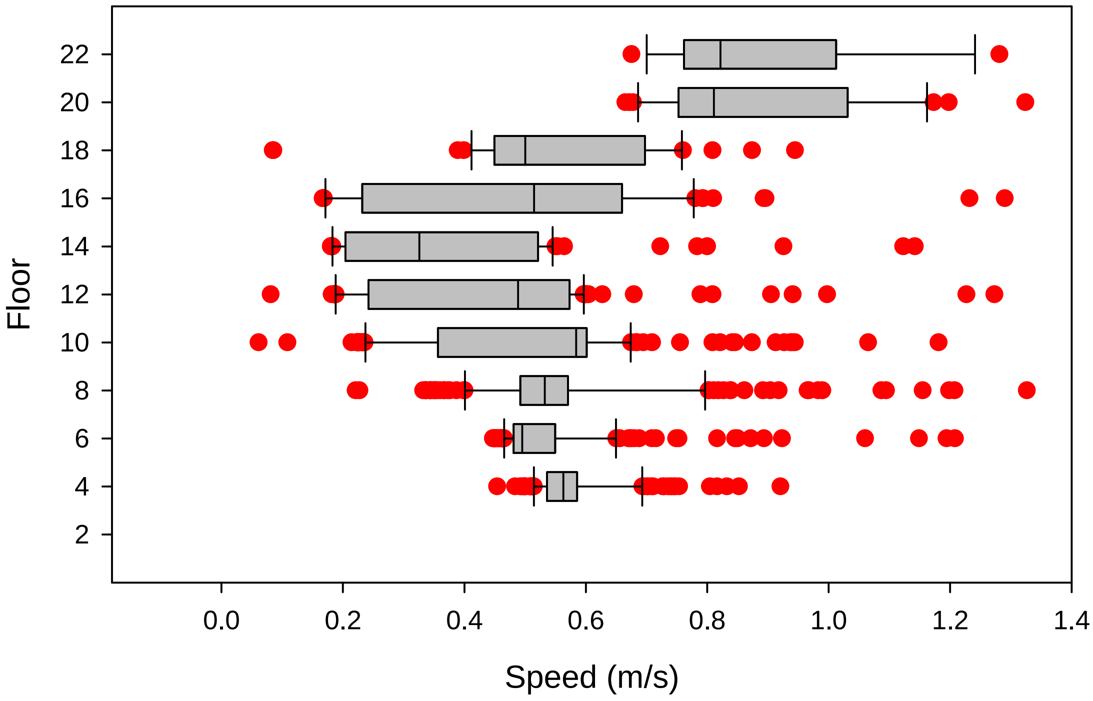


Stair 3 E

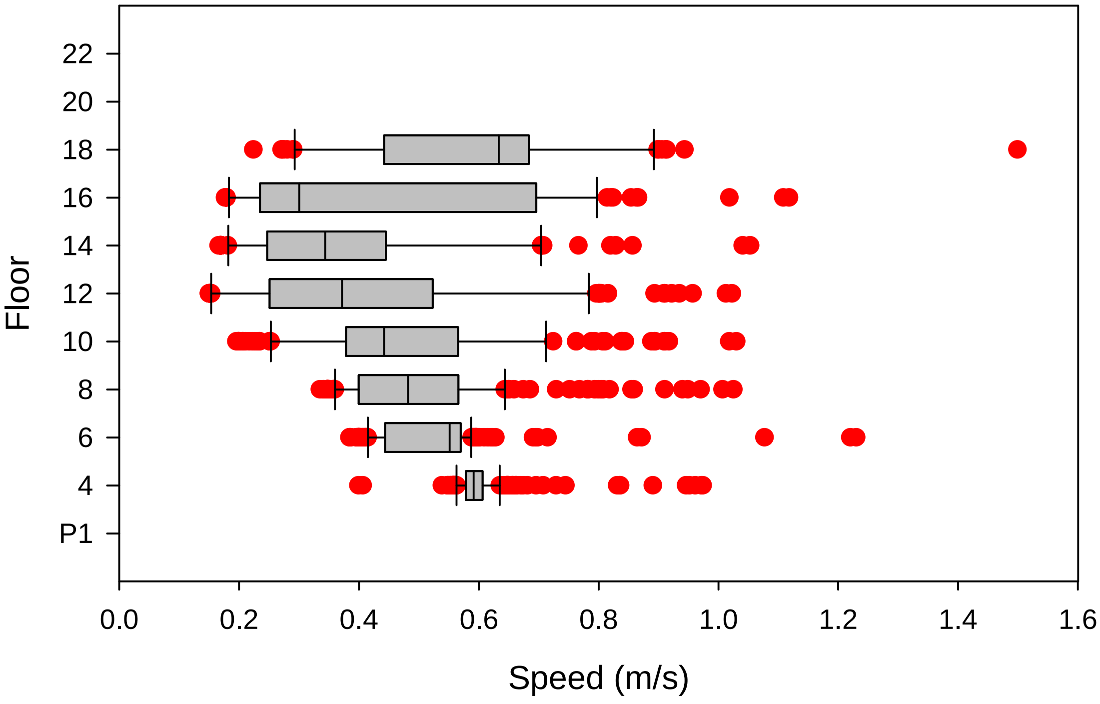


Stair 3 W

Figure C-3. Local Movement Speeds for All Camera Locations in Building 3

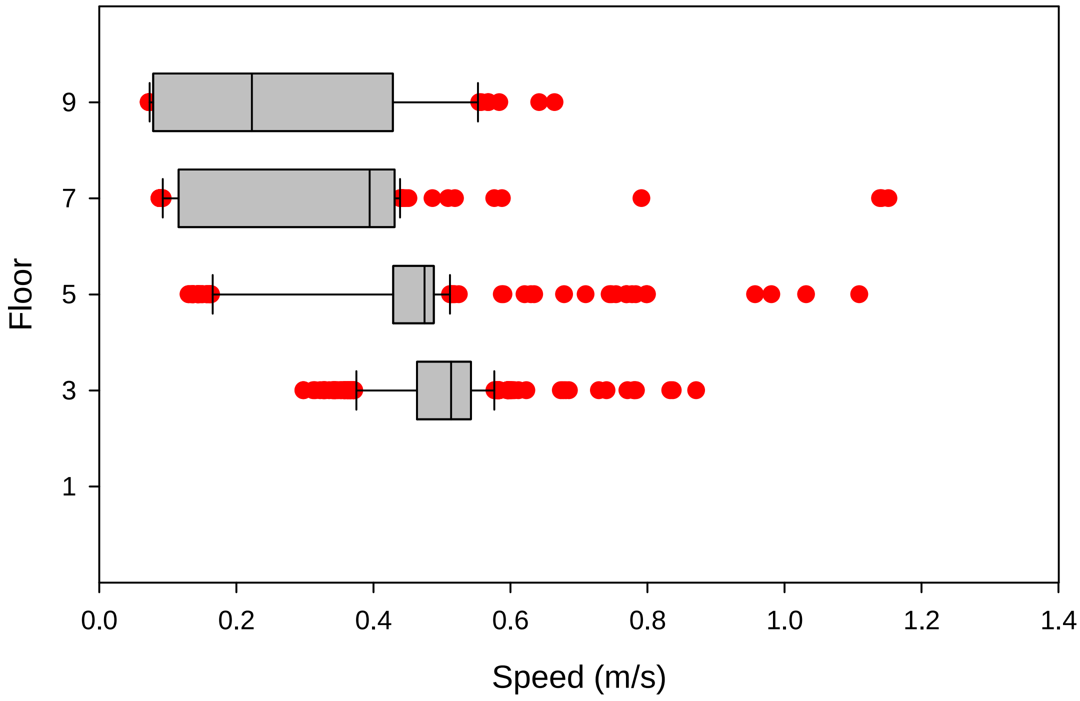


Stair 4 A

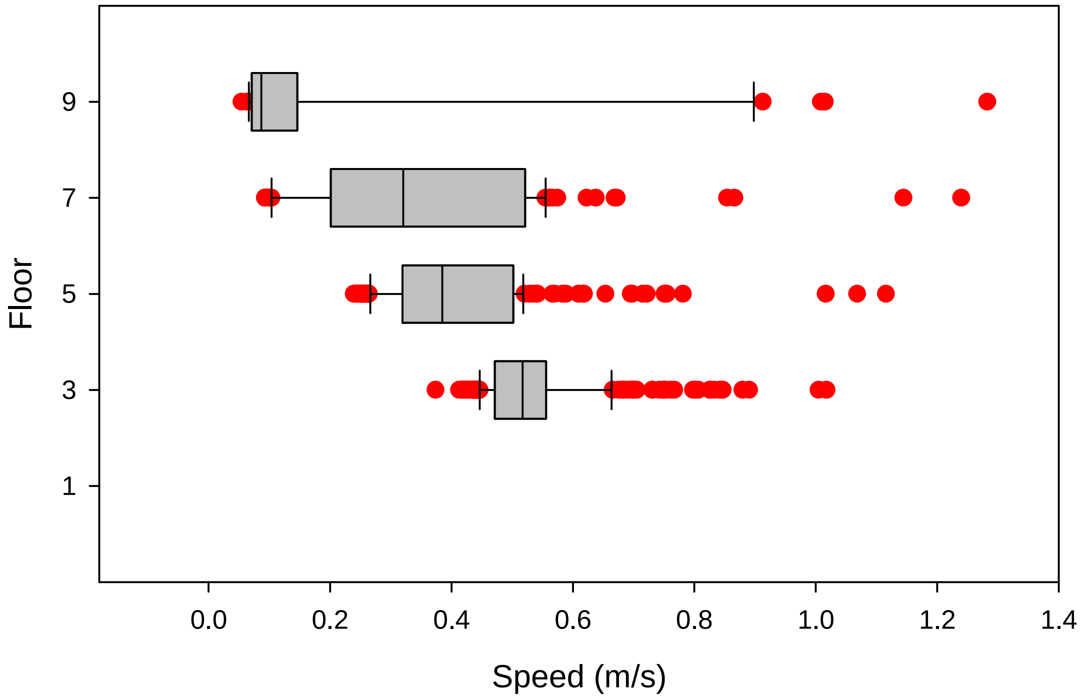


Stair 4 B

Figure C-4. Local Movement Speeds for All Camera Locations in Building 4

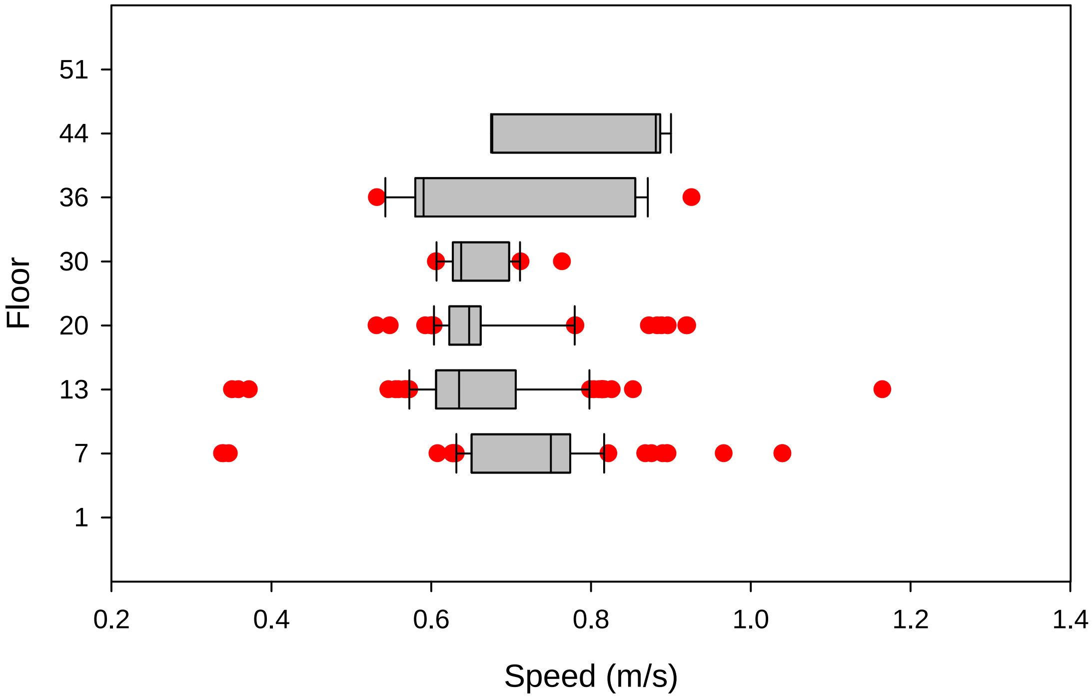


Stair 5 A

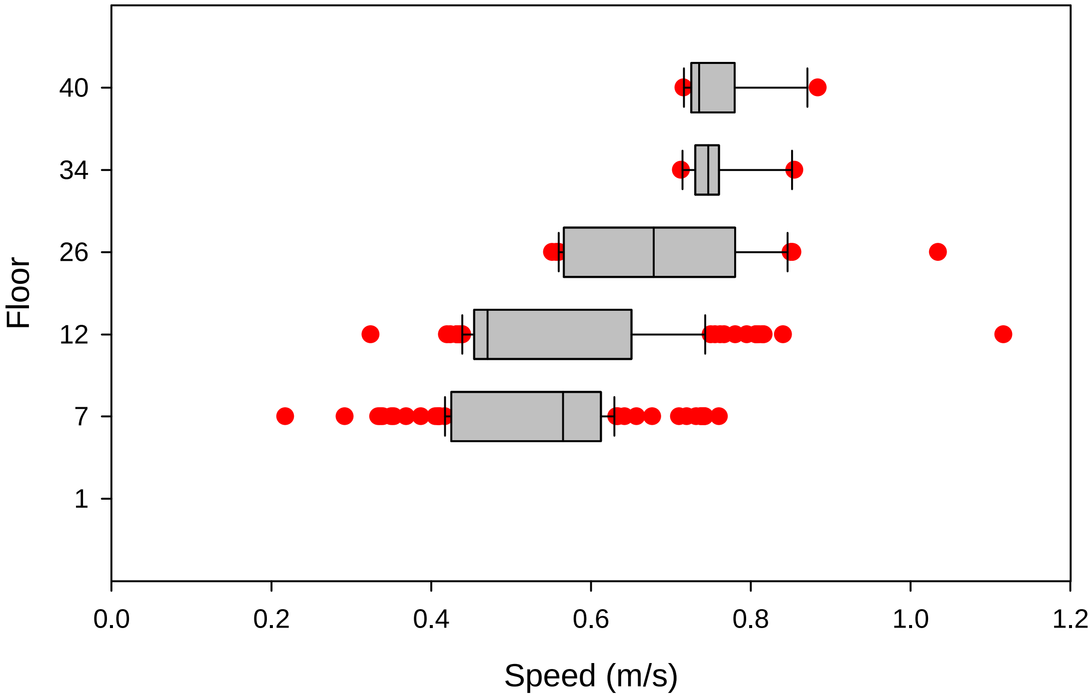


Stair 5 B

Figure C-5. Local Movement Speeds for All Camera Locations in Building 5

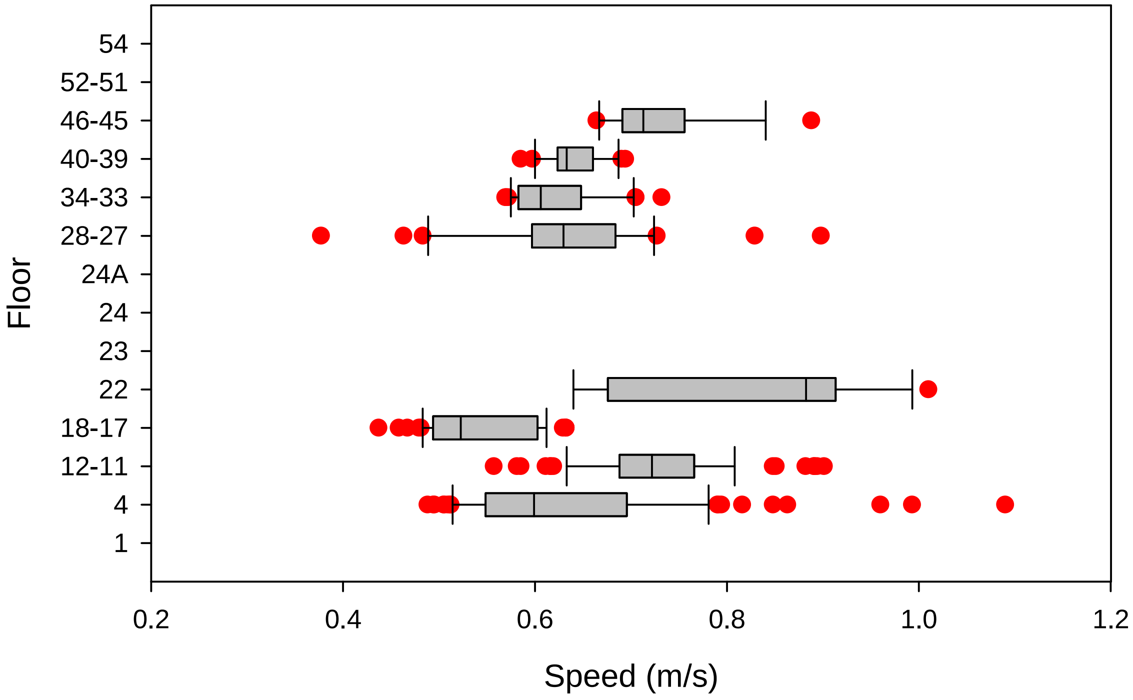


Stair 6-5

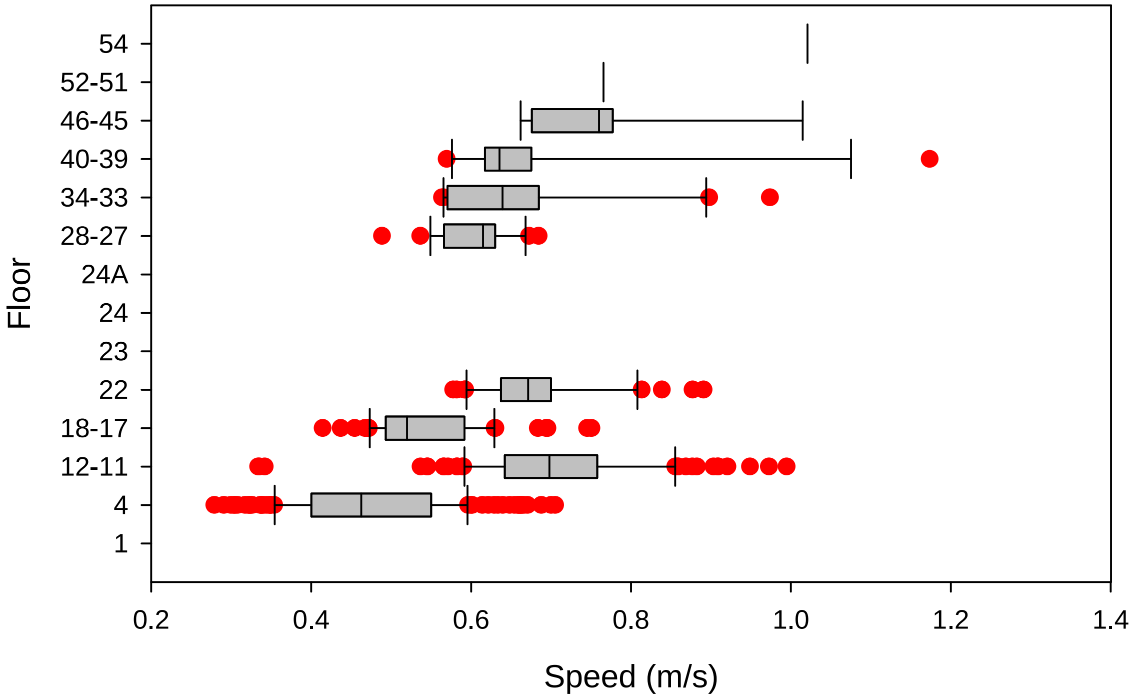


Stair 6-5A

Figure C-6. Local Movement Speeds for All Camera Locations in Building 6

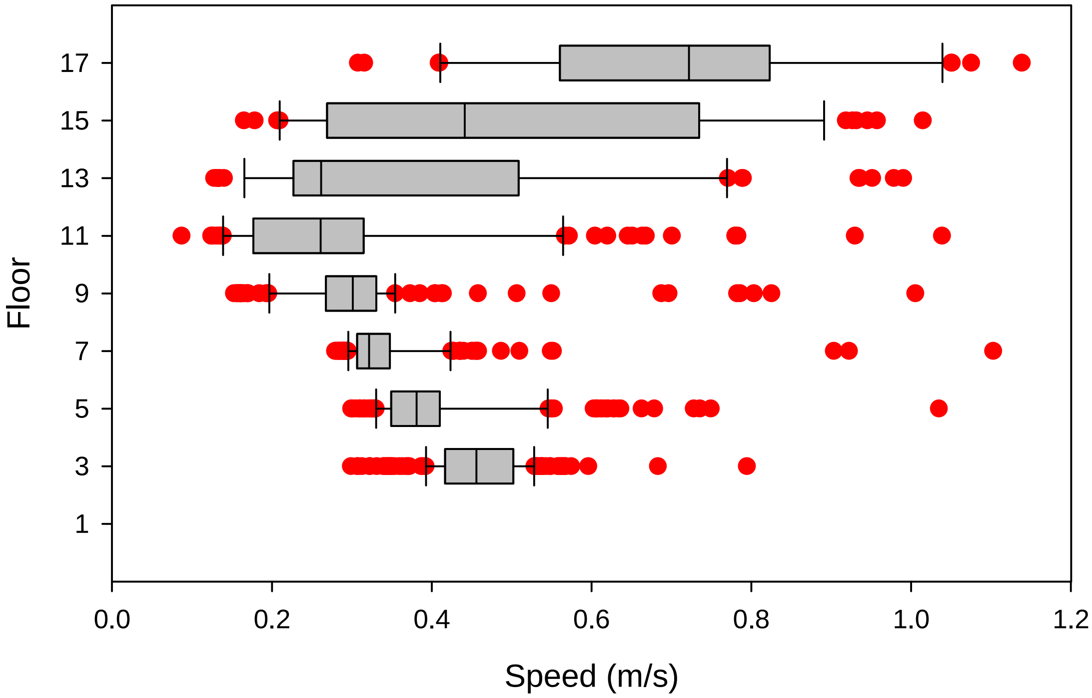


Stair 6-6

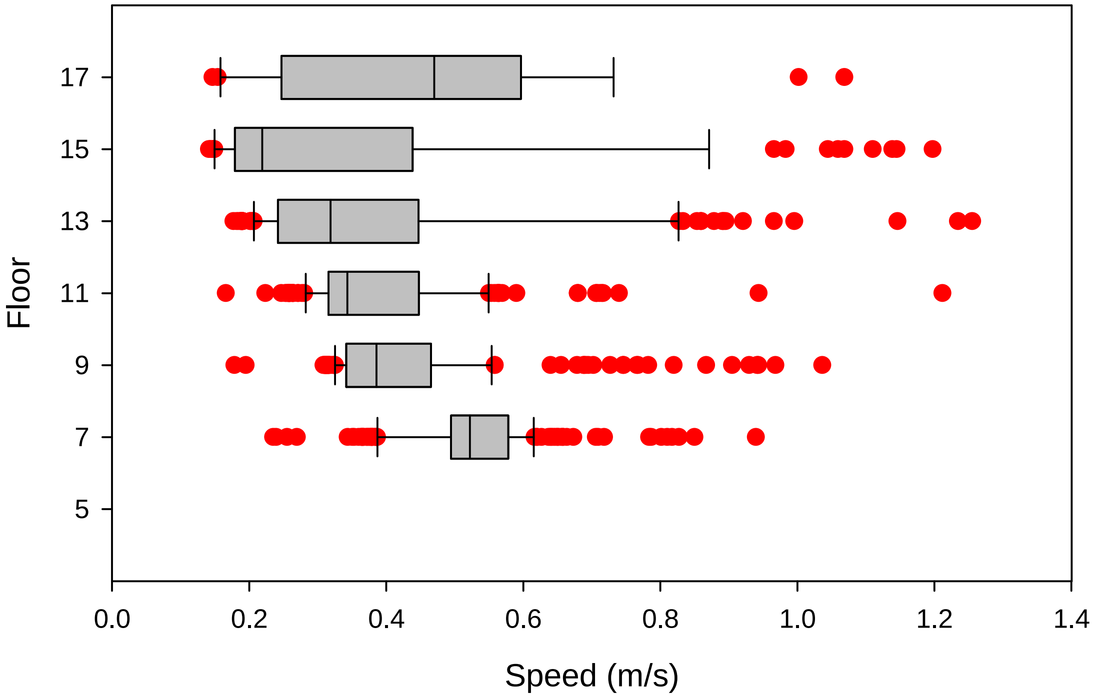


Stair 6-6A

Figure C-6. Local Movement Speeds for All Camera Locations in Building 6, continued

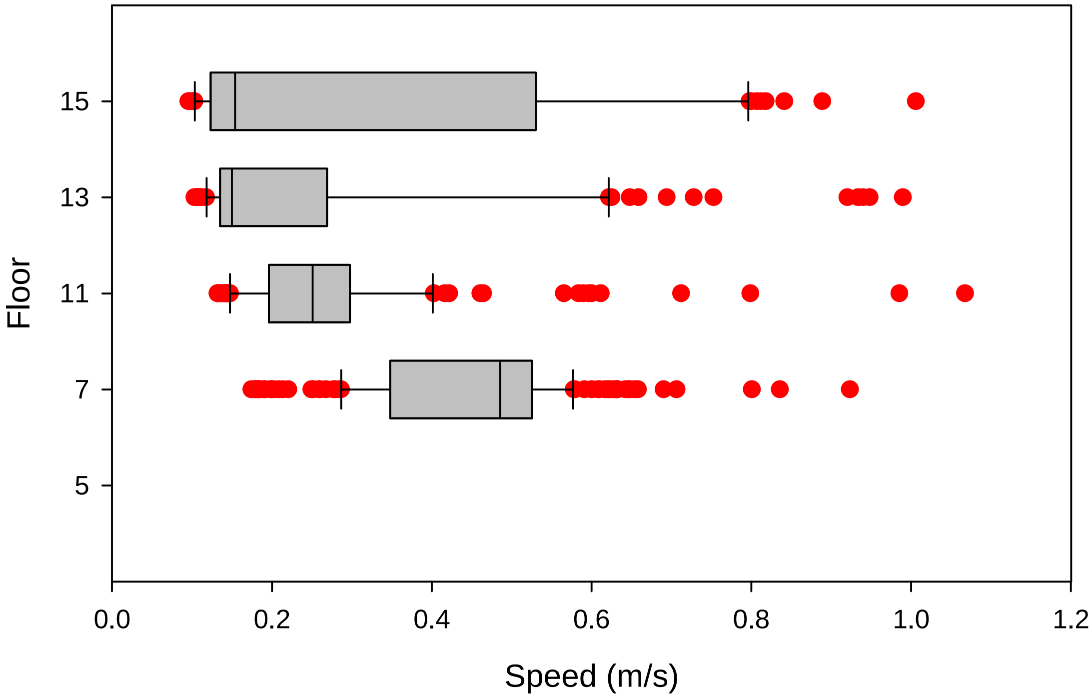


Stair 7-1

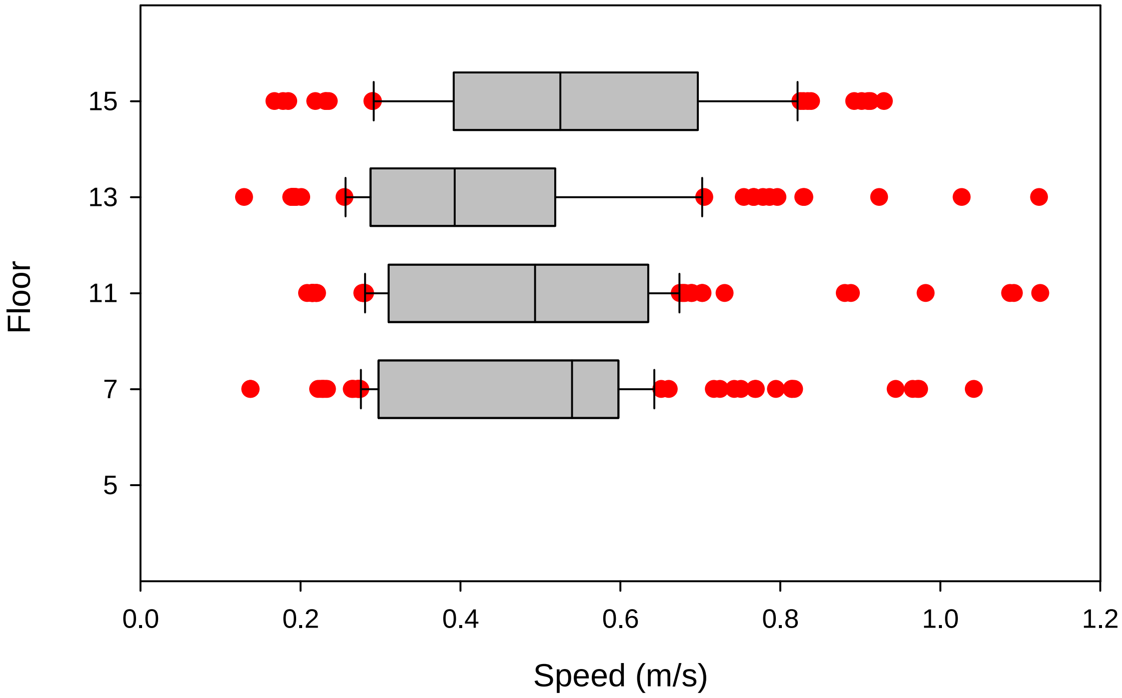


Stair 7-3

Figure C-7. Local Movement Speeds for All Camera Locations in Building 7

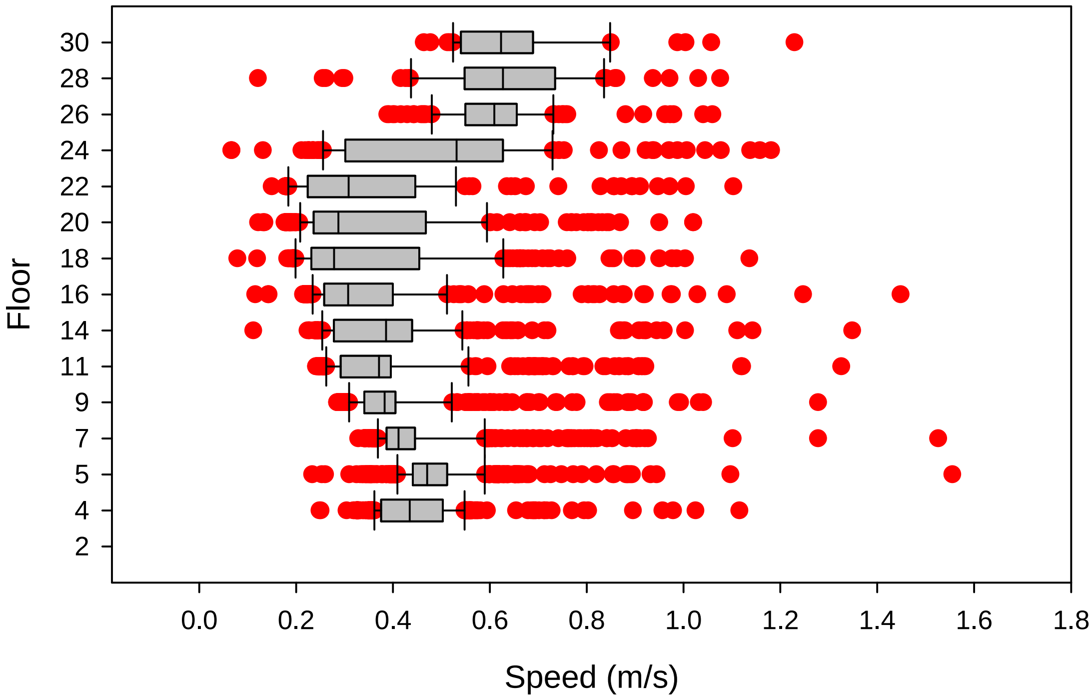


Stair 7-7

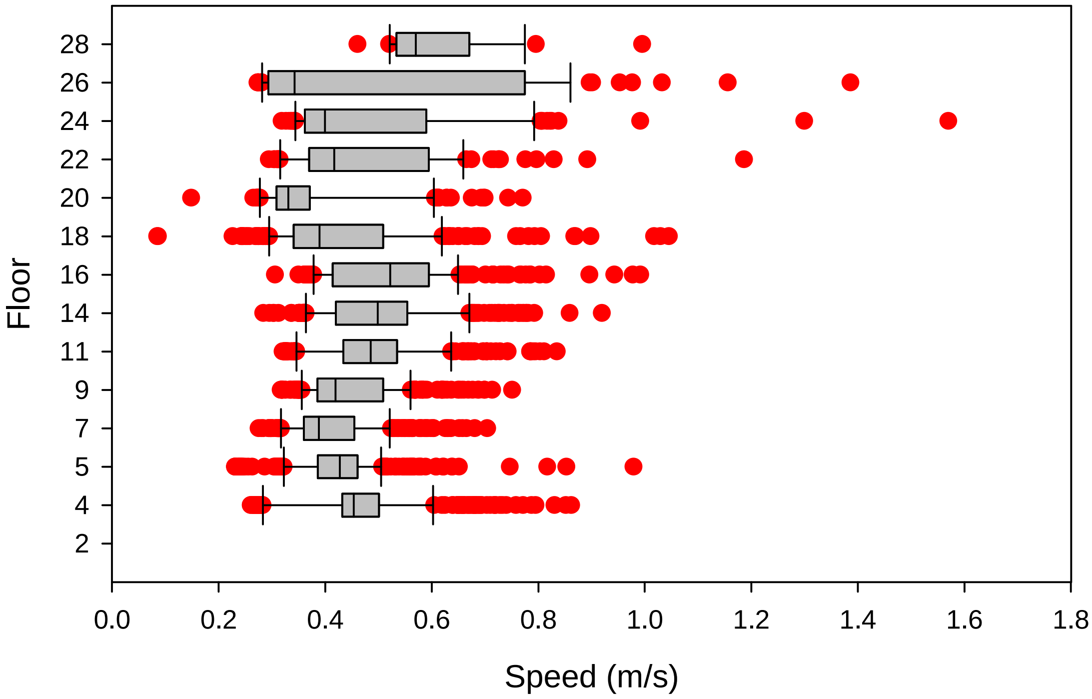


Stair 7-12

Figure C-7. Local Movement Speeds for All Camera Locations in Building 7, continued

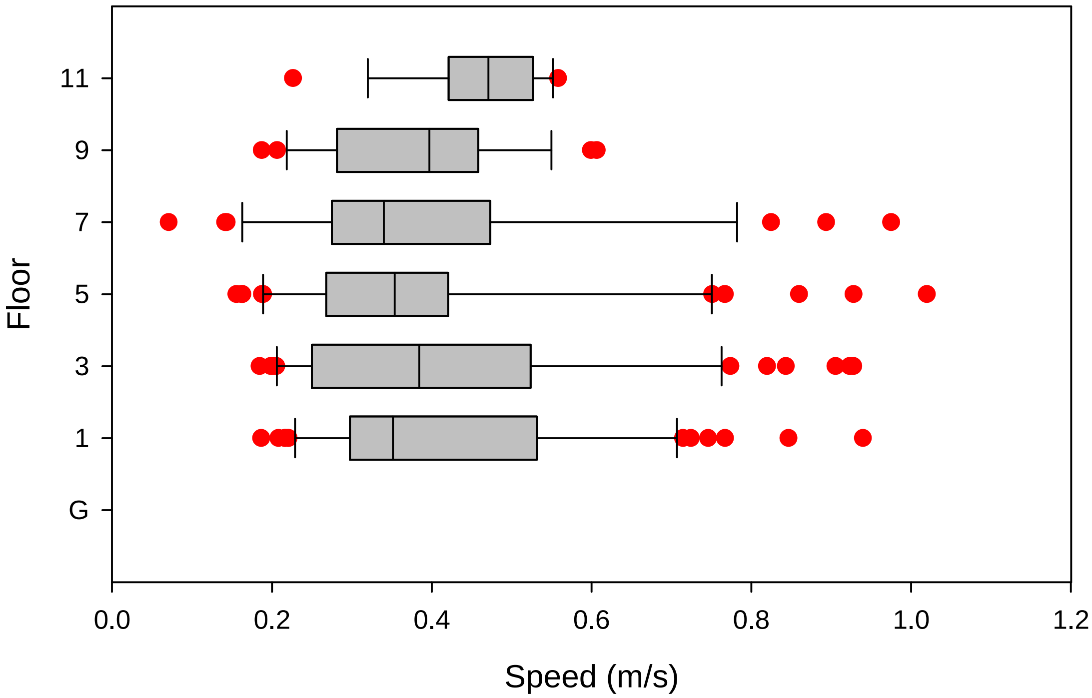


Stair 8 N

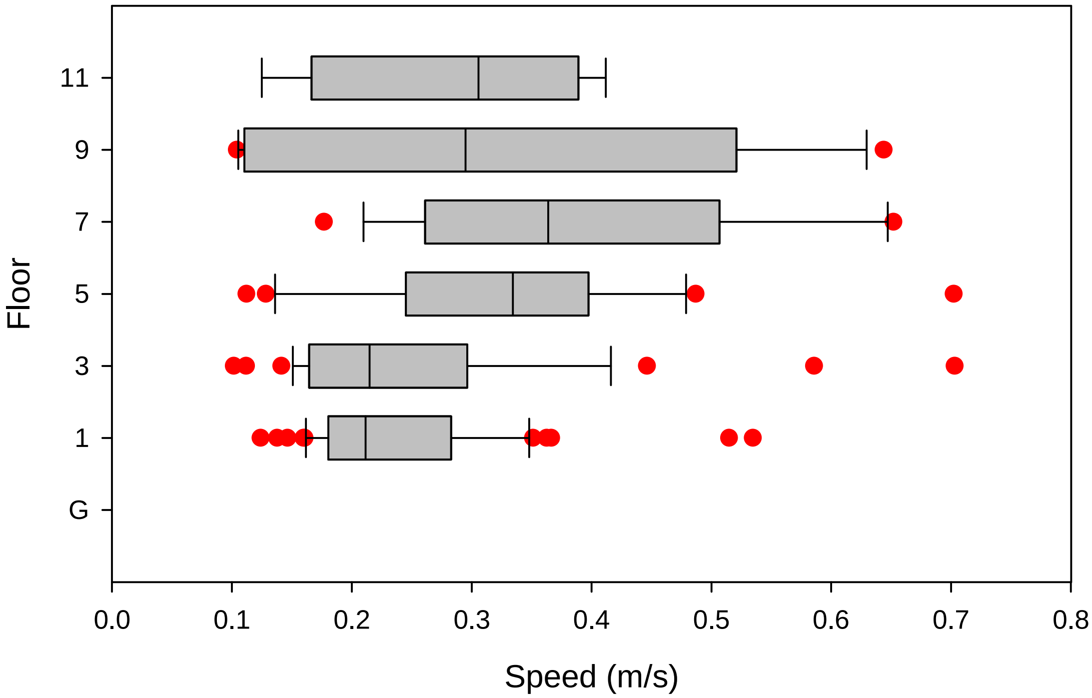


Stair 8 S

Figure C-8. Local Movement Speeds for All Camera Locations in Building 8

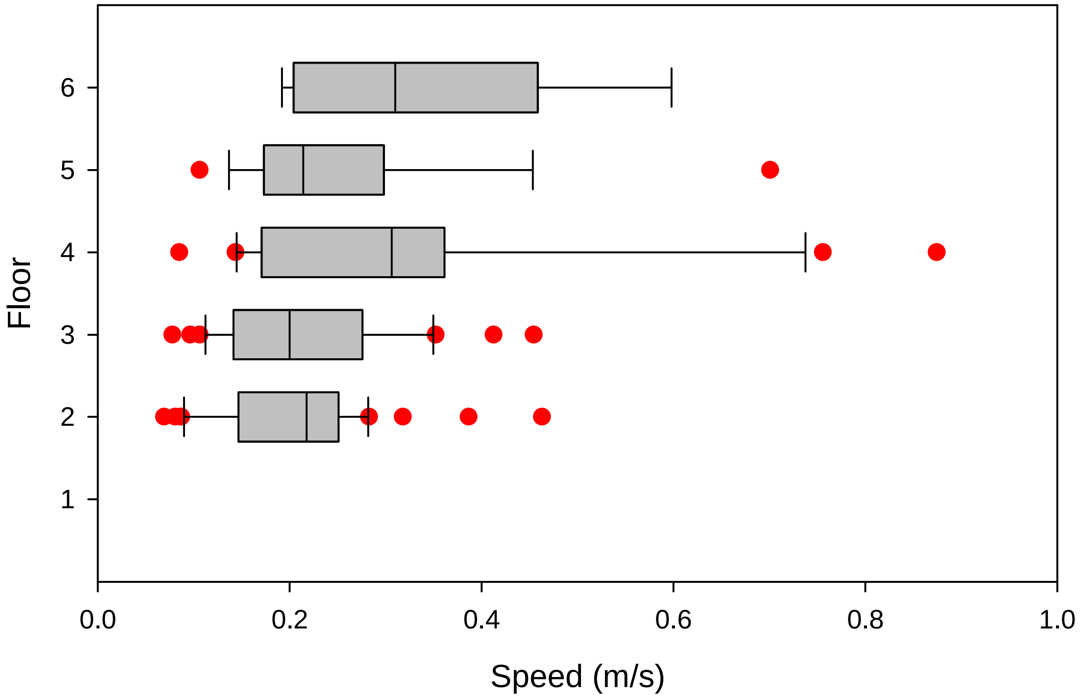


Stair 9 A



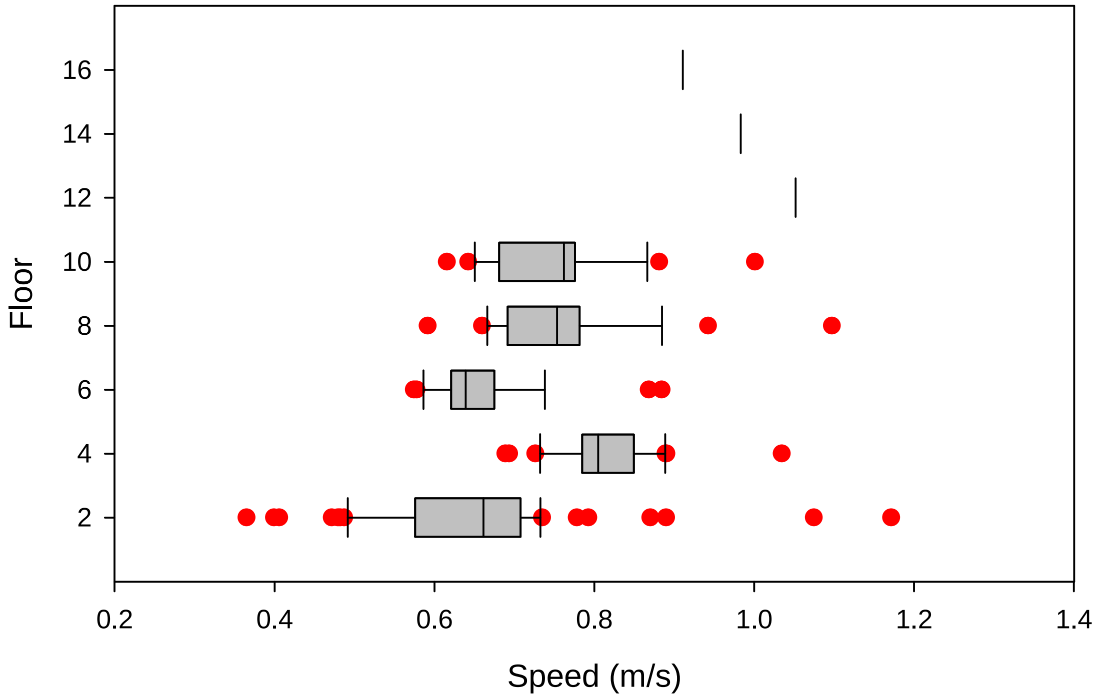
Stair 9 B

Figure C-9. Local Movement Speeds for All Camera Locations in Building 9

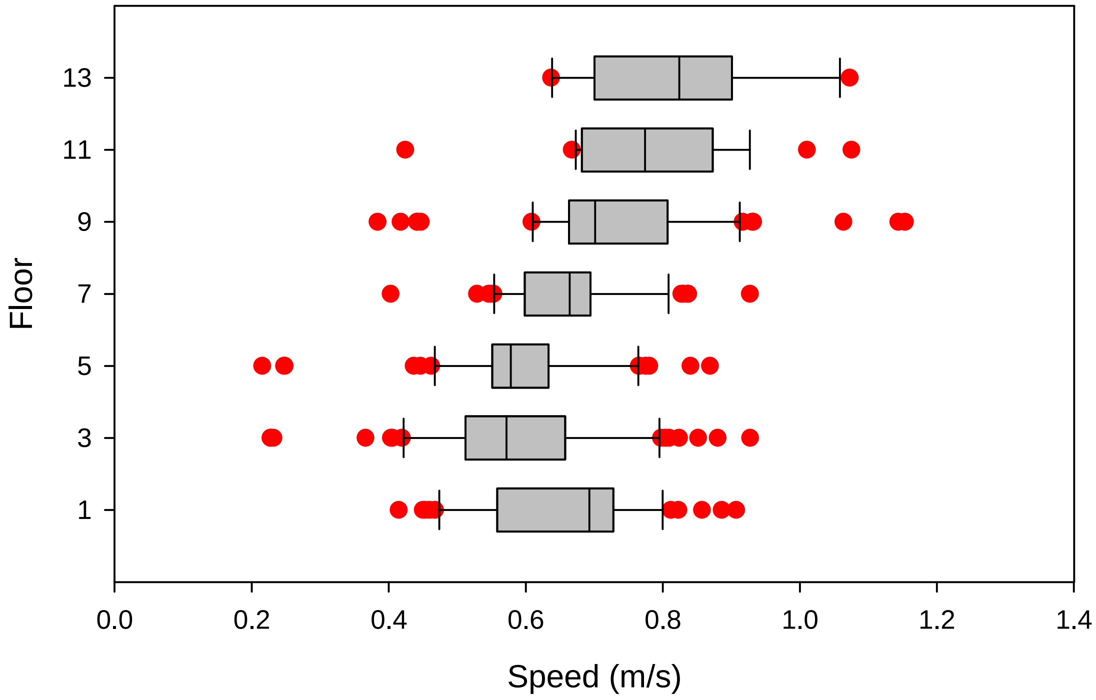


Stair 10-2

Figure C-10. Local Movement Speeds for All Camera Locations in Building 10

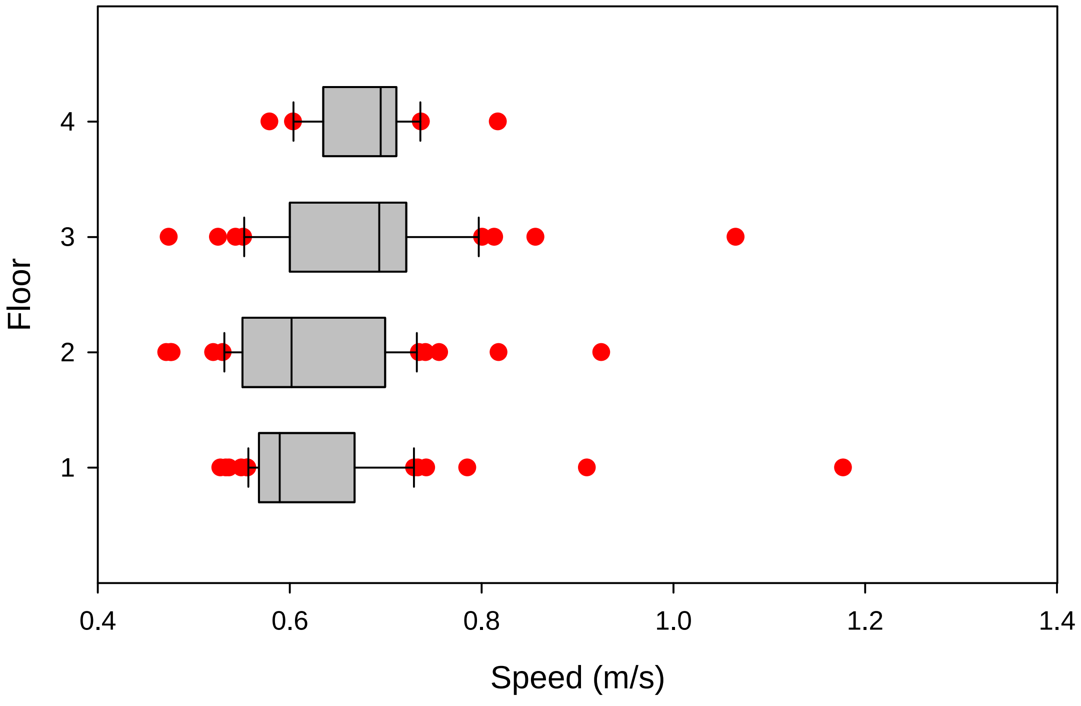


Stair 11-2

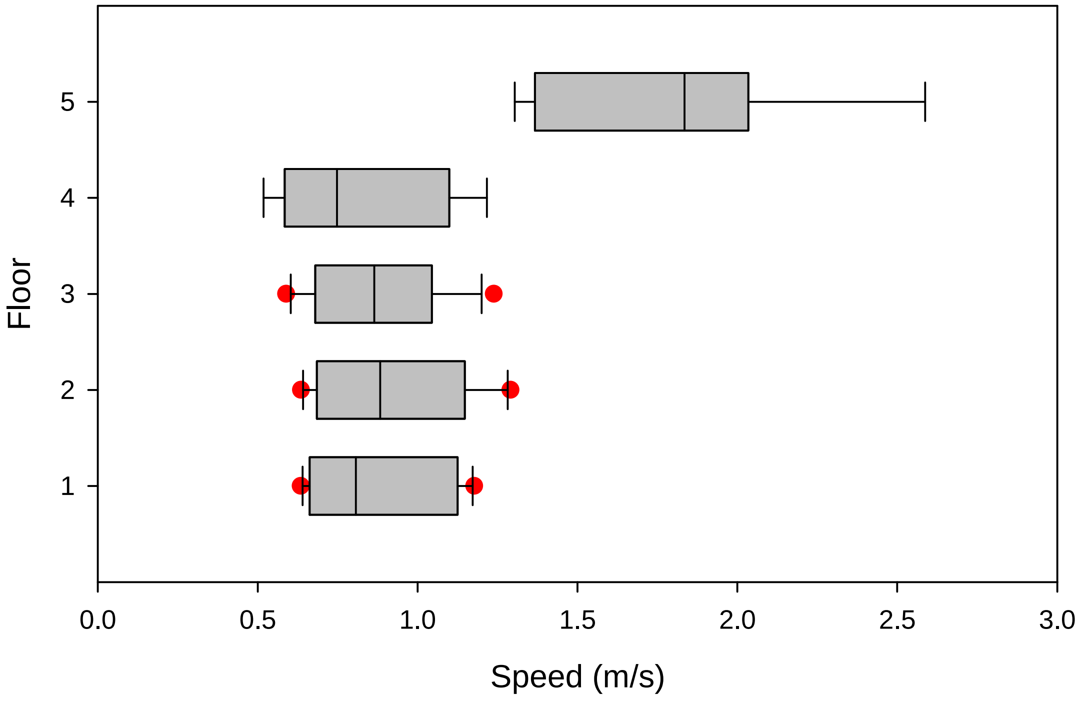


Stair 11-3

Figure C-11. Local Movement Speeds for All Camera Locations in Building 11

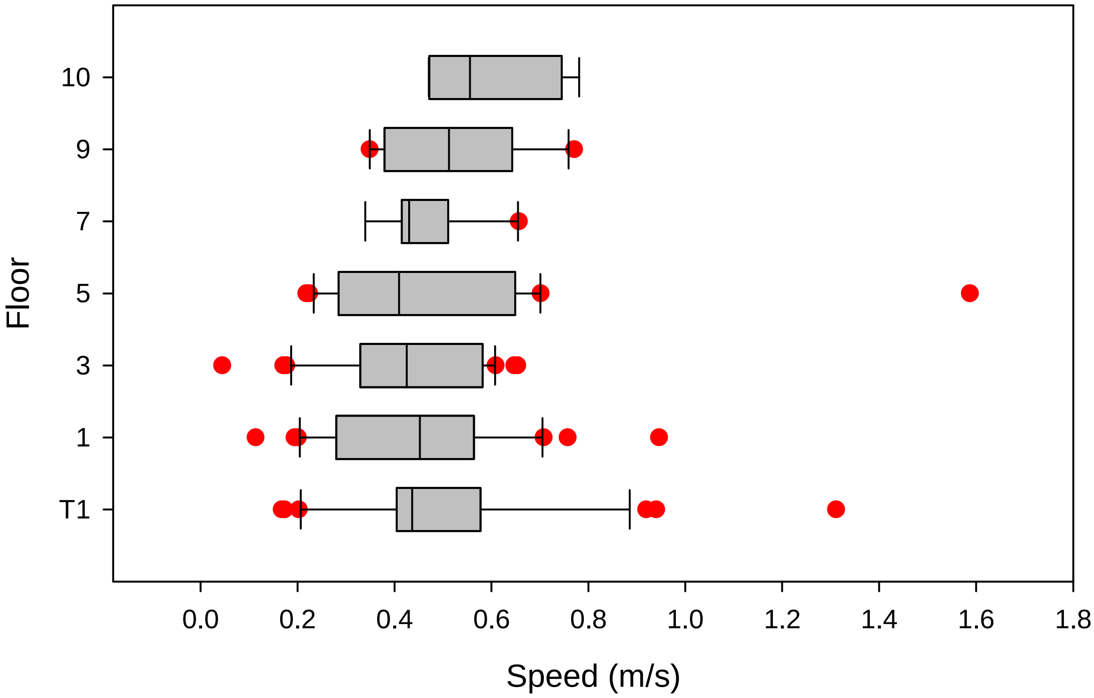


Stair 12 A

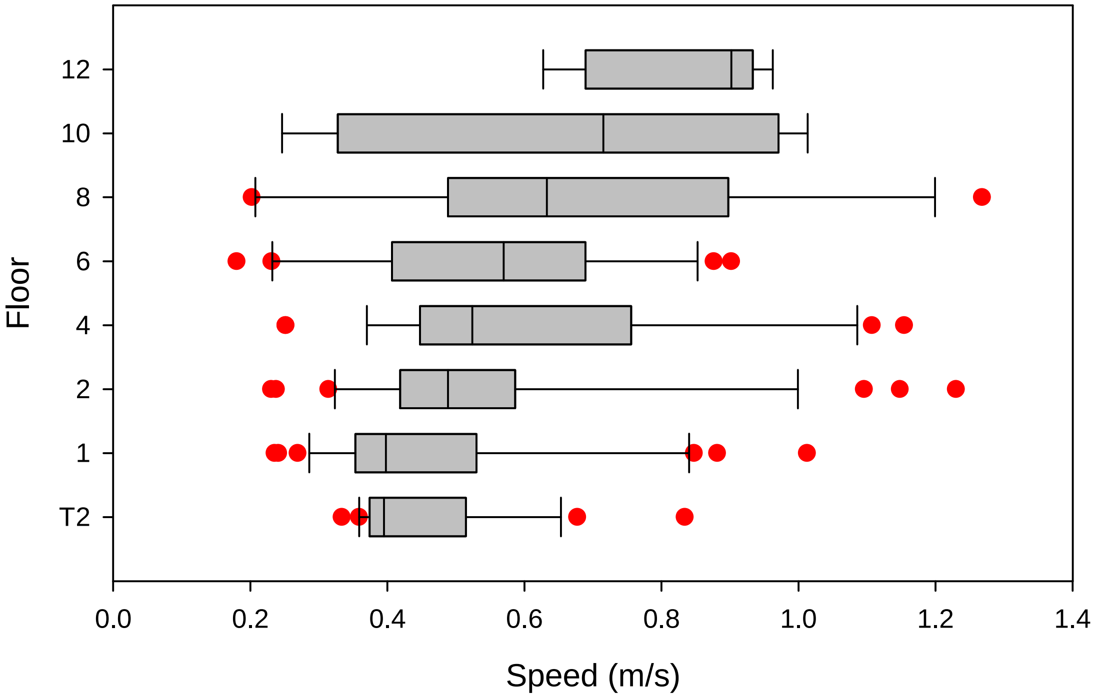


Stair 12 B

Figure C-12. Local Movement Speeds for All Camera Locations in Building 12

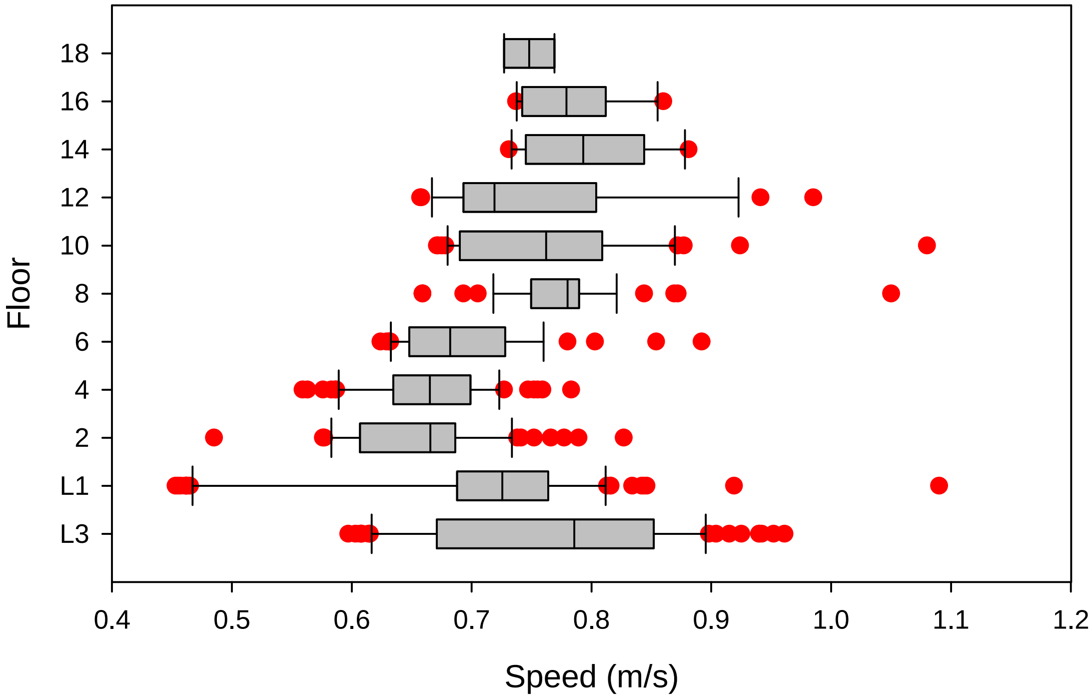


Stair 13-1

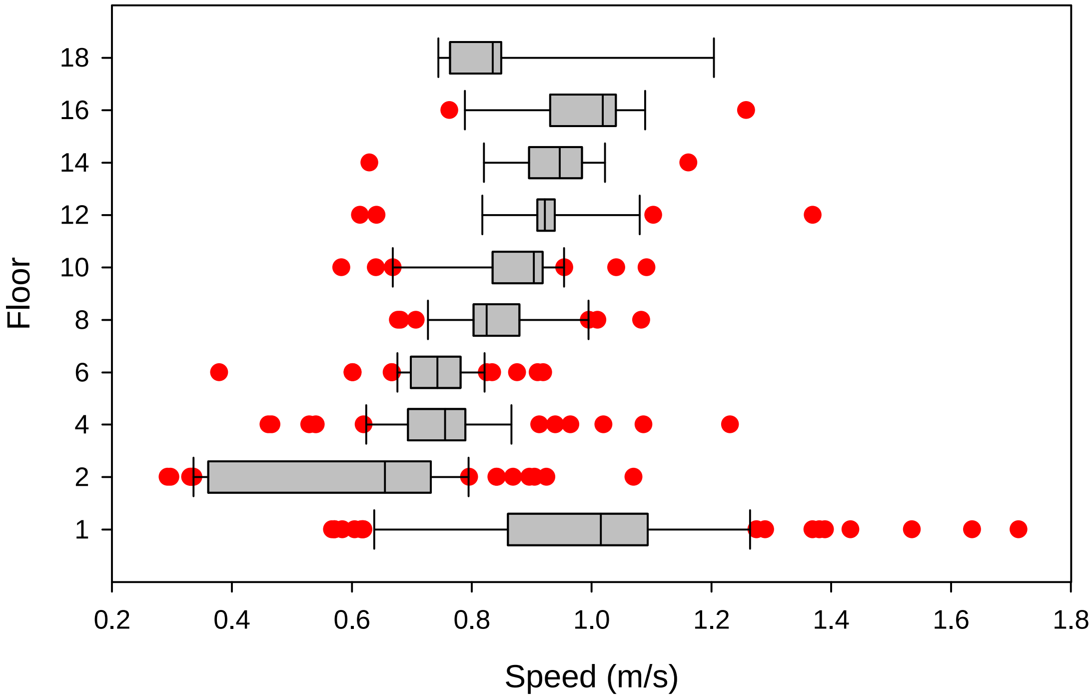


Stair 13-2

Figure C-13. Local Movement Speeds for All Camera Locations in Building 13



Stair 14-1



Stair 14-2

Figure C-14. Local Movement Speeds for All Camera Locations in Building 14

D. Parameter Estimation using Linear Least Squares and Bayesian Inference

In Sections 4.5 and 4.6, we explore correlations and functional relationships between engineering variables of interest and occupant flow, speed, pre-observation time, and exit time using parameter estimation. Two approaches will be used. One approach to conduct parameter estimation is to use optimization methods, such as linear least squares, to determine a single solution for an unknown parameter that best fits the data. This is known as a frequentist approach to parameter estimation. In the frequentist approach, the data are considered to be random observations, and the unknown parameters are considered to be fixed but unknown constants. This approach has some limitations when working with a limited data set that has an inherent amount of noise. Additionally, the resulting confidence intervals do not quantify the amount of credibility of the unknown parameters.

The second approach used considers the observations as coming from a distribution depending on an unknown parameter θ. In addition to the observations, it is assumed that there is a distribution P(θ) that describes the location of θ_0. P(θ) is called the prior distribution about θ before observations are taken. This approach is known as Bayesian inference, which uses Bayes' theorem [1] to combine our knowledge of prior information and observed data to form a resulting posterior distribution of an unknown parameter. The results of a Bayesian inference procedure is a probability distribution that contains uncertainty information of every plausible parameter value after observing the data [1]. Additionally, the resulting credible intervals are a range of parameter values that contain the true parameter value, which is directly interpretable and more applicable than confidence intervals.

D.1 Bayesian Inference

Consider the outcomes of two events, Outcome A and Outcome B. The probability of these outcomes is represented as $P(A)$ and $P(B)$. The conditional probability of Outcome A given Outcome B is represented as $P(A|B)$. Central to Bayesian inference is Bayes' theorem, which can be used to compute $P(A|B)$ is given by

$$P(A|B) = \frac{P(B \mid A) \cdot P(A)}{P(B)} \tag{1}$$

where $P(A|B)$ is the posterior quantity, $P(B|A)$ is the likelihood, and $P(B)$ is the normalizing constant. In practical applications, the normalizing constant $P(B)$ is difficult to compute, and thus the posterior quantity is often described in terms of a proportionality as

$$P(A|B) \propto P(B \mid A) \cdot P(A) \tag{2}$$

For the applications considered in this study, Outcome *A* corresponds to unknown model parameters θ_i, and Outcome *B* corresponds to observed data *D* and a model *M*. Thus, we can rewrite Eq. (2) as

$$P(\theta_i \mid D, M) \propto P(D \mid \theta_i, M) \cdot P(\theta_i \mid M) \tag{3}$$

which states that the probability of the unknown parameters producing observed data using the model $P(\theta_i|D,M)$ (posterior) is proportional to the probability of obtaining the observed data using the model and unknown parameters $P(D|\theta_i,M)$ (likelihood) multiplied by the probability of the occurrence of the unknown parameters given a model $P(\theta_i|M)$ (prior). A summary of the Bayesian inference procedure is shown in Figure D-1. More details on the Bayesian inference process are described in reference [2].

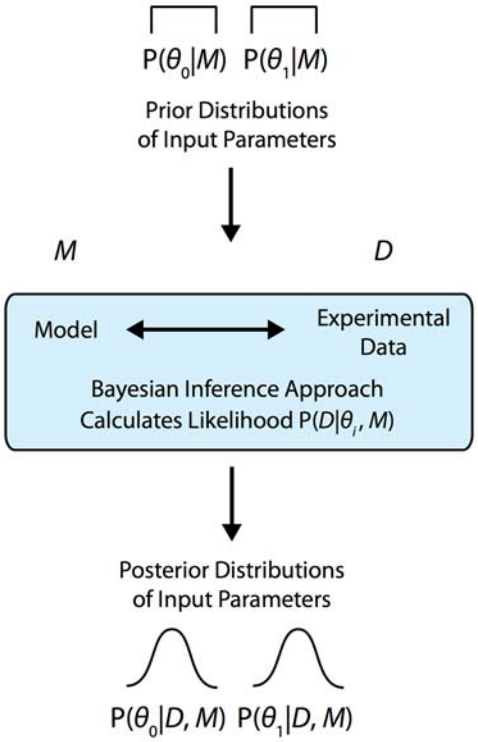


Figure D-1. Overview of Bayesian inference process.

The computational framework used in this study included the following tools for data processing, analysis, and visualization: Python 2.7.5, NumPy 1.7.1, SciPy 0.12.0, matplotlib 1.3.0, and PyMC 2.2. Python is a high-level, flexible, and powerful programming language that is well-suited to scientific and engineering applications [3]. NumPy is a package for scientific computing in Python and includes efficient methods for working with arrays, tools for integrating Python, C, C++, and Fortran code, and linear algebra functionality [4]. SciPy is a counterpart to NumPy and includes routines for efficient numerical integration and optimization as well as statistical analysis tools [5]. The matplotlib package is a 2D plotting library for Python [6].

The PyMC module is used for Bayesian inference and is summarized as [7]

> PyMC is a Python module that implements Bayesian statistical models and fitting algorithms, including Markov chain Monte Carlo. Its flexibility and extensibility make it applicable to a large suite of problems. Along with core sampling functionality, PyMC includes methods for summarizing output, plotting, goodness-of- fit and convergence diagnostics.

The Python module PyMC computes and reports the posterior mean, median, quartiles, and standard deviation for each unknown parameters θ_i. Additionally, all parameter values in the posterior distribution are saved in PyMC, and the NumPy and SciPy packages in Python can then be used to compute other statistical quantities of interest.

One of the useful tools that are available making use of the LLS approach is p-value. One may think of a p-value as the probability (likelihood) that the magnitude of a test statistic associated with a hypothesis test under consideration occurred merely by chance. A small p-value indicates that the data provide evidence that the null hypothesis is false. Because of the limited number of tests and the inherent variability in people we will be using a standard cut off for the p-value of 0.1.

D.2 Example Application

In this section, the linear least squares and Bayesian methods for parameter estimation are applied, in detail, to one of the functional relationships described in section 4.5. At the end of the section, the results for the other 6 relationships are presented without the level of detail included for the first example. For Model 1, we consider the relationship between the average flow (of the middle 90 % of non-residential stairs) and the total population. The data are shown in Figure D-2 for all non-residential stairs (one data point per stair).

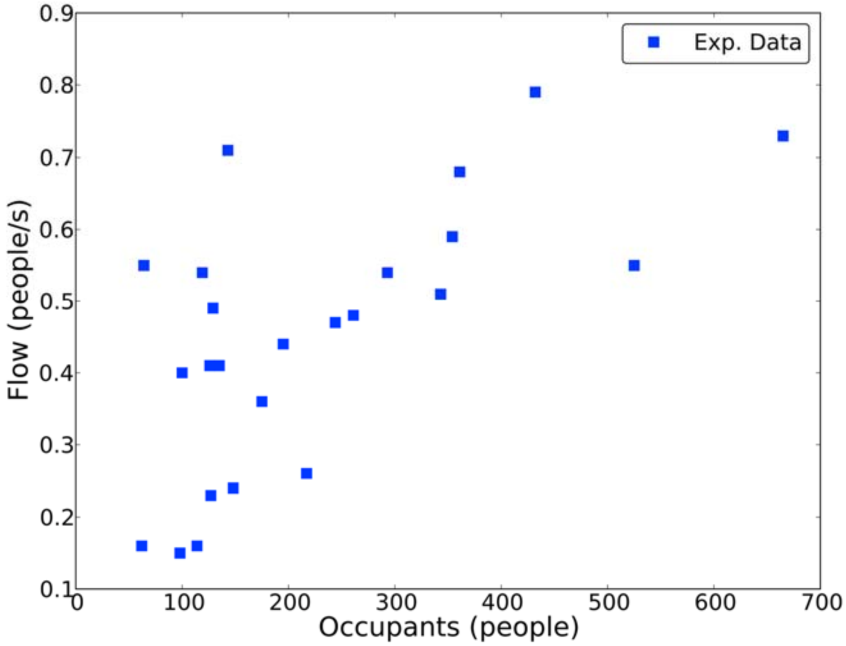


Figure D-2. Flow vs. total population

It is assumed that the average flow is correlated to the total population by a power law relationship, $F_{ave} = \theta_0 P_{total}^{\theta_1}$.

The Bayesian inference procedure was set up using PyMC with 1 000 000 iterations. The first 800 000 iterations were discarded to allow for the parameter search process to converge to a region of high probability for the unknown parameters. This setting is known as the burn-in period. Of the final 200 000 iterations, only every 200th sample was retained, which helps to reduce repeated parameter samples that can skew the resulting posterior distribution. This setting is known as the thinning parameter. For this case and all of the remaining, the same settings were used: 1 000 000 total iterations, a burn-in period of 800 000, and a thinning parameter of 200.

The prior distributions of the unknown parameters were specified as uniform distributions as follows: [-10, 10] for θ_0, and [-5, 5] for θ_1. Bayesian inference, making use of the posterior distributions of the unknown parameters θ_0 and θ_1 and the data shown in Figure D-, was performed. The resulting posterior distributions, parameter traces, and autocorrelation plots are shown in Figure 3.

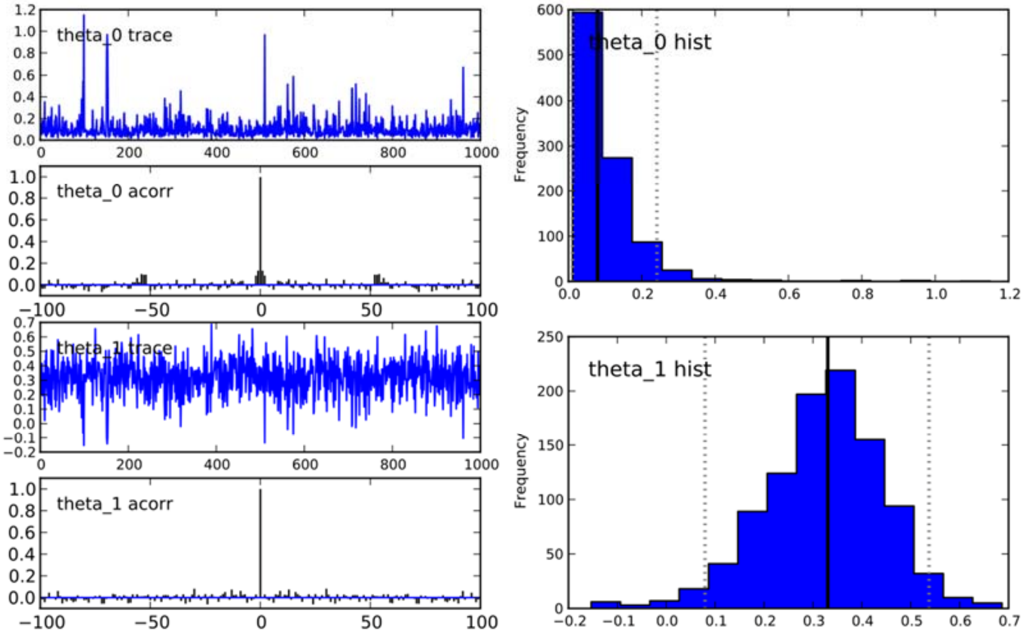


Figure D-3. Parameter traces, autocorrelation plots, and posterior distributions of unknown parameters

In Figure D-3, the top left plot (parameter trace) shows the value of θ_0 throughout the PyMC simulation, which appears to explore a region of high probability centered on a value of 0.1. The bottom left plot shows the autocorrelation of the parameter trace, which summarizes repeated values (i.e., lags) during the parameter search process. The results of this autocorrelation plot indicate good results of the parameter search process, with minimal amounts of lag. Finally, the plot on the right side shows a histogram of the values in the posterior distribution.

In this case, the posterior median values for θ_0 and θ_1 are 0.07 and 0.34, respectively. The 95 % credible intervals for θ_0 and θ_1 are [0.02, 0.26] and [0.12, 0.59], respectively. The 95 % credible interval is the range of values that has a 95 % probability of containing the true values of θ_0 and θ_1.

The values for the parameters θ_0 and θ_1 from the posterior distributions were used in the model, and the resulting model iterations are shown in Figure D-4. In this figure, the gray lines represent individual model predictions over all values in the posterior distribution, and the solid green line represents the model prediction using the posterior mean value of θ_0 and θ_1.

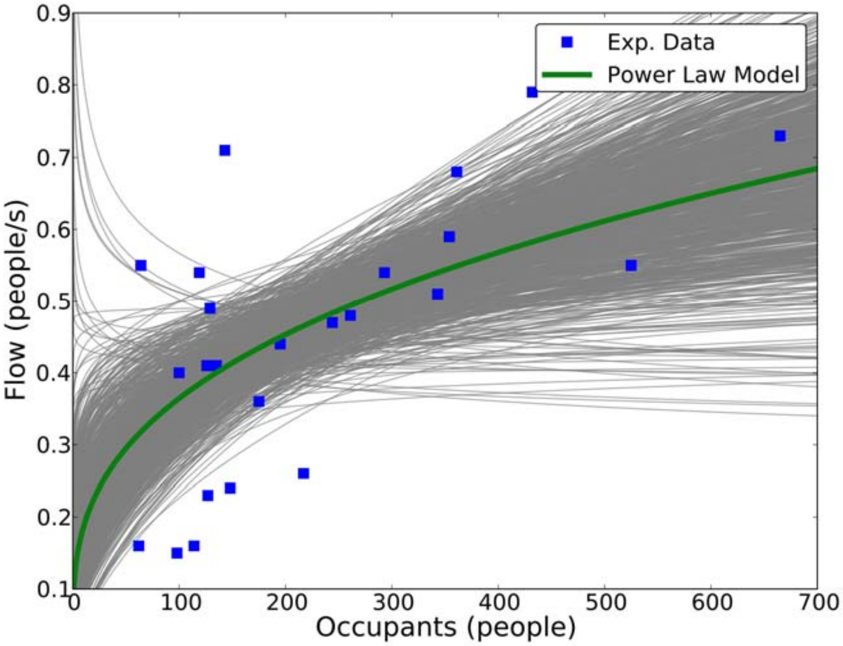


Figure D-4. Results of Model 1 evaluated at the posterior mean value (solid green line) and for all values from the posterior distribution of θ_0 and θ_1 (gray lines)

The gray region formed by the individual realizations represents a qualitative uncertainty in the model predictions given our uncertainty in the unknown parameters. With additional observed data points or models that better describe the observed data, a reduction in the propagated model uncertainty would be expected.

Finally, the deviance information criterion (DIC) can be used to quantify relative performance between different models, which can be used to perform model selection. The DIC is calculated as

$$DIC = p_D + \overline{D}$$

where p_D is the effective number of parameters, and $\overline{D}$ is the deviance, or a measure of how well the model fits the data (similar to the R^2 value in frequentist inference methods like LLS). In a relative comparison of models, the model with the lowest DIC value is preferred. In this case, the DIC value was -30.0.

Total population is correlated with average flow (of the middle 90% of non-residential stairs) via linear least squares. The correlations for θ_0 and θ_1 are 0.037 and 0.46. The R^2 is 0.40. Figure D-5 shows the correlation of total population to average flow for both methods.

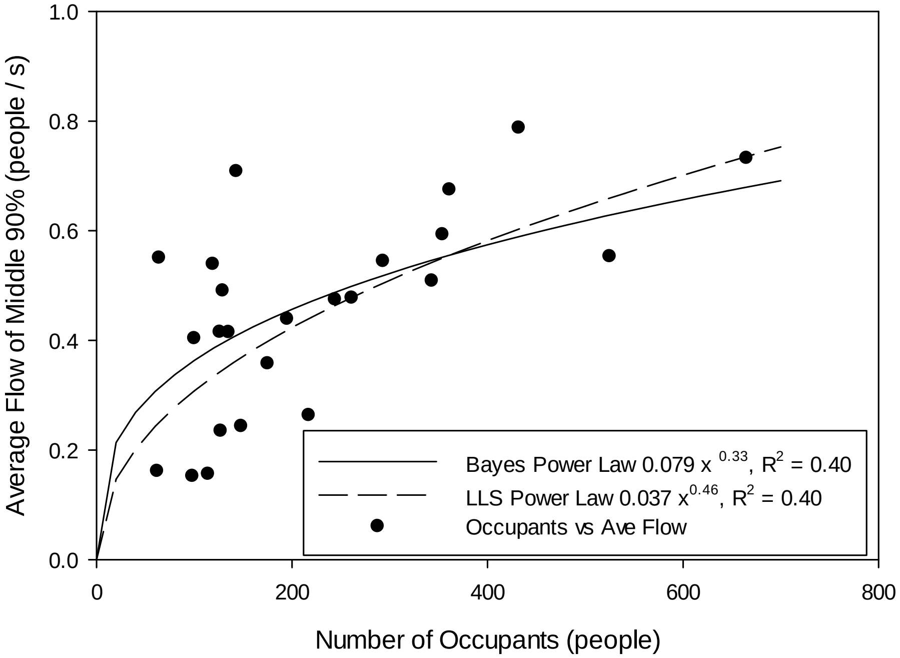
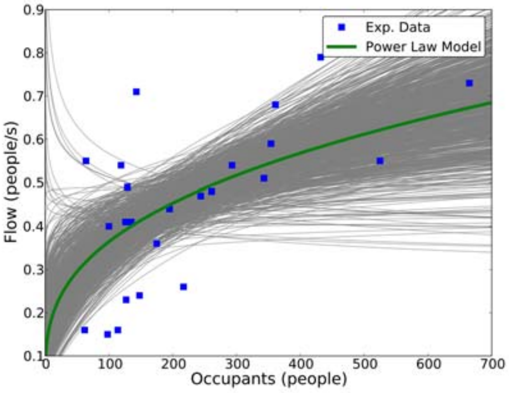
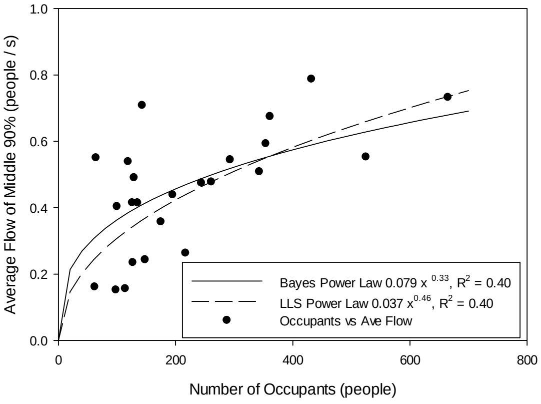


Figure D-5. Average flow vs. number of occupants and the Bayesian and Linear Least Squares fits

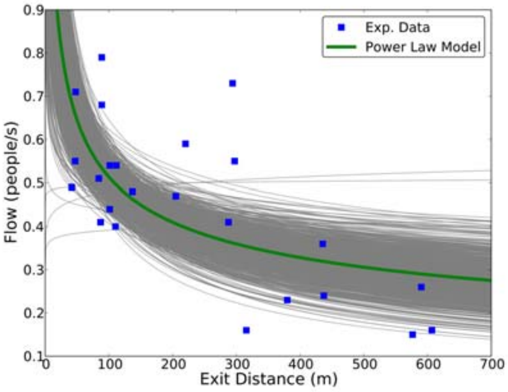
Note that for both θ_0 and θ_1 the values generated by LLS fall within 95% confidence intervals found using Bayesian inference. Both parameters are found to be significant in LLS. A graphical summary of the analysis for all seven functional relationships included in Section 4.5 is shown in Figure D-6.



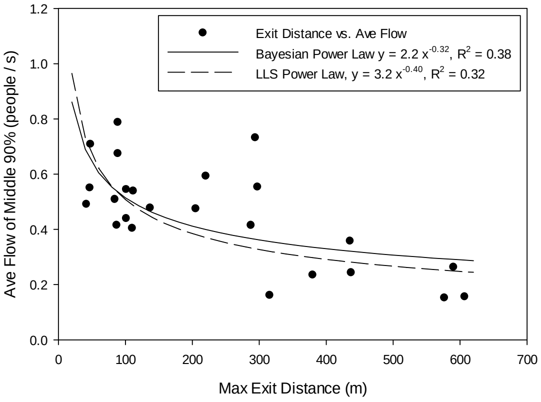
Model 1, $F_{ave} = \theta_0 P_{total}^{\theta_1}$, Bayesian Inference with all values from posterior distribution



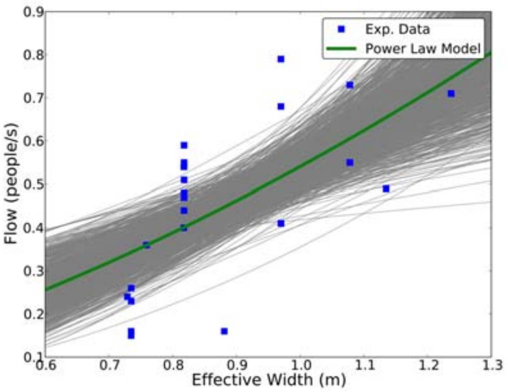
Model 1, $F_{ave} = \theta_0 P_{total}^{\theta_1}$, results from Bayesian and Linear Least Squares Fits



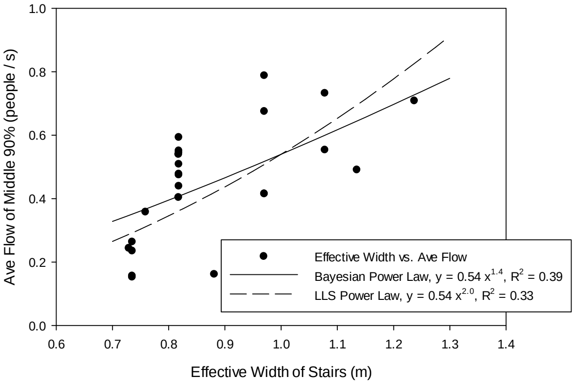
Model 2, $F_{ave} = \theta_0 D_{exit}^{\theta_1}$, Bayesian Inference with all values from posterior distribution



Model 2, $F_{ave} = \theta_0 D_{exit}^{\theta_1}$, results from Bayesian and Linear Least Squares Fits

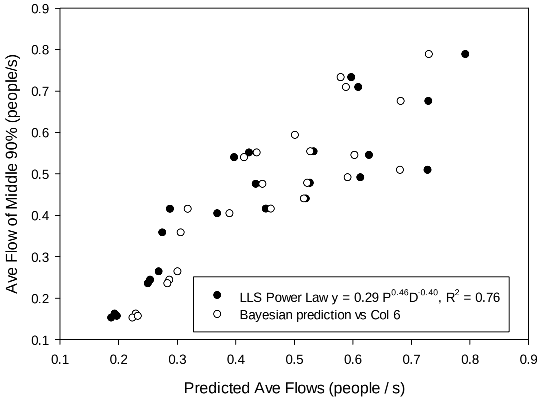


Model 3, $F_{ave} = \theta_0 w_{eff}^{\theta_i}$, Bayesian Inference with all values from posterior mean

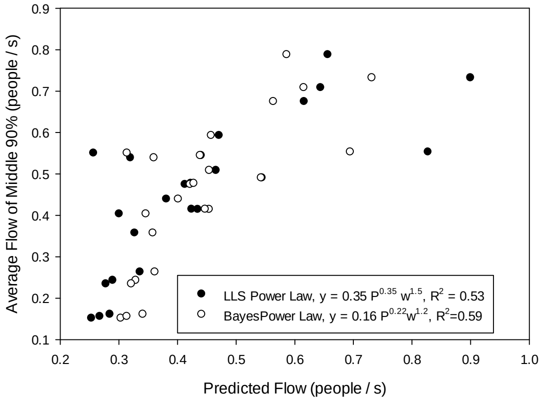


Model 3, $F_{ave} = \theta_0 w_{eff}^{\theta_i}$, Results from Bayesian and Linear Least Squares Fits

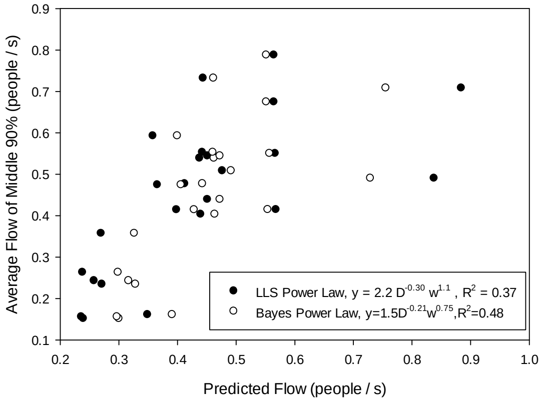
Figure D-6. Results for 7 models determined by Bayesian Inference and Linear Least Squares



Model 4, $F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2}$, Results from Bayesian and Linear Least Squares Fits

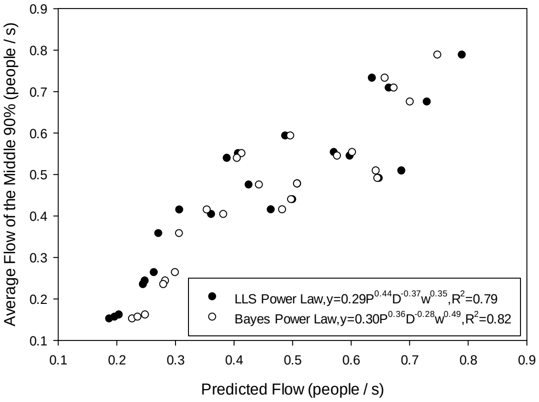


Model 5, $F_{ave} = \theta_0 P_{total}^{\theta_1} w_{eff}^{\theta_2}$, Results from Bayesian and Linear Least Squares Fits



Model 6, $F_{ave} = \theta_0 D_{exit}^{\theta_1} w_{eff}^{\theta_2}$, Results from Bayesian and Linear Least Squares Fits

Figure D-6. Results for 7 models determined by Bayesian Inference and Linear Least Squares, continued



Model 7, $F_{ave} = \theta_0 P_{total}^{\theta_1} D_{exit}^{\theta_2} w_{eff}^{\theta_3}$, Results from Bayesian and Linear Least Squares Fits

Figure D-6. Results for 7 models determined by Bayesian Inference and Linear Least Squares, continued

1. W.M. Bolstad. Understanding Computational Bayesian Statistics. John Wiley & Sons Inc., 2010.
2. Overholt, K. J., “Forward and Inverse Modeling of Fire Physics Towards Fire Scene Reconstructions.” Ph.D. dissertation, The University of Texas at Austin, 2013.
3. T.E. Oliphant. “Python for Scientific Computing.” *Computing in Science & Engineering*, 9(3):10–20, May-June 2007.
4. T.E. Oliphant. A Guide to NumPy, volume 1. Trelgol Publishing USA, 2006.
5. E. Jones, T. Oliphant, P. Peterson, and others. “SciPy: Open source scientific tools for Python,” 2001–.

6 J. Hunter. “Matplotlib: A 2D graphics environment.” Computing In Science & Engineering, 9(3):90–95, 2007.

7 A. Patil, D. Huard, and C. Fonnesbeck. “PyMC: Bayesian Stochastic Modelling in Python.” *Journal of Statistical Software*, 35(4):1–81, 7 2010.

E. Point Process Modeling

An egress flow past an exit door can be represented by a sequence of ordered, irregularly spaced time points $t_1 < t_2 < \ldots < t_n$ lying on the real line. In general, for a point process, these event times represent the occurrences of some random event. A point process, *N(t)*, is a statistical description of the information in these events. Let *N(t)* represent the number of events that have occurred by time *t* and for $s < t$, let $N(t) - N(s)$ represents the number of events having occurred in the time interval $(s,t]$. That is,

$$N(t) = \#\{t_i < \mathrm{t}, i = 1, \ldots, n\}\,. \tag{1}$$

The simplest and most familiar point process is the Poisson process described by

$$P\left[N(T) = k\right] = \frac{(\lambda t)^k}{k!} e^{-\lambda t} \qquad k = 0,1,2,\ldots \tag{2}$$

The parameter λ is called the Poisson rate, because it describes the number of events occurring per unit time. The mean number of events occurring in the time interval $(0,t]$ is λt. This process is called a homogeneous Poisson process since λ is independent of *t*. An example of a Poisson process is the arrival times of customers at a train depot. The more general nonhomogeneous Poisson process allows the rate to depend on *t*, say $\lambda = \lambda(\mathrm{t})$ and the probability of *k* events occurring in $(0,t]$ is given by

$$P\left[N(T) = k\right] = \frac{\left(m(t)\right)^k}{k!} e^{-m(t)} \qquad k = 0,1,2,\ldots \quad \text{where} \quad m(t) = \int_0^t \lambda(s)\,ds \tag{3}$$

$m(t)$ is the mean number of events occurring in $(0,t]$ and $\lambda(t)$ is the infinitesimal expected rate of events at *t*. Cinlar [89] contains information about Poisson processes.

The most general rate function depends at time *t* on the past history of the process data [90]. To this end, denote by $\mathcal{H}_{\mathrm{t}} = \sigma\{t_1, t_2, \ldots, t_k : t_i < t\}$ the past history of the process, i.e., all events depending on the event times occurring up to time t. Then $\lambda = \lambda(t \mid \mathcal{H}_t)$ is called the conditional intensity of the point process. It is defined by

$$\lambda\left(t \middle| \mathcal{H}_t\right) = \lim_{\delta \downarrow 0} \frac{1}{\delta t} E\left[\frac{N(t+\delta t) - N(t)}{\delta t} \middle| \mathcal{H}_t\right] \tag{4}$$

or equivalently, for point process where no two events can occur at the same time, by

$$\lambda\left(t \middle| \mathcal{H}_t\right) = \lim_{\delta \downarrow 0} \frac{1}{\delta t} P\left[N(t+\delta t) - N(t) = 1 \middle| \mathcal{H}_t\right] \tag{5}$$

By definition eq. (4), the conditional intensity $\lambda(t \mid \mathcal{H}_t)$ is the density of the conditional mean intensity $E[N(t) \mid \mathcal{H}_t]$ (not necessarily a probability density).

The data in this study are not event times for a homogeneous Poisson process. The inter-arrival times $t_i - t_{i-1}$, $i=1,\ldots,n$, $t_0 = 0$ for a homogeneous Poisson process are independent and exponentially distributed with mean λ. Travel and pre-observation times are highly correlated for egress data, due to the occupant to occupant interaction on the floor and within the stair. Sample traces of exit times (i.e., times at which people reach the exit location for the building) for four stairs included in this study are shown in Figure E-1.

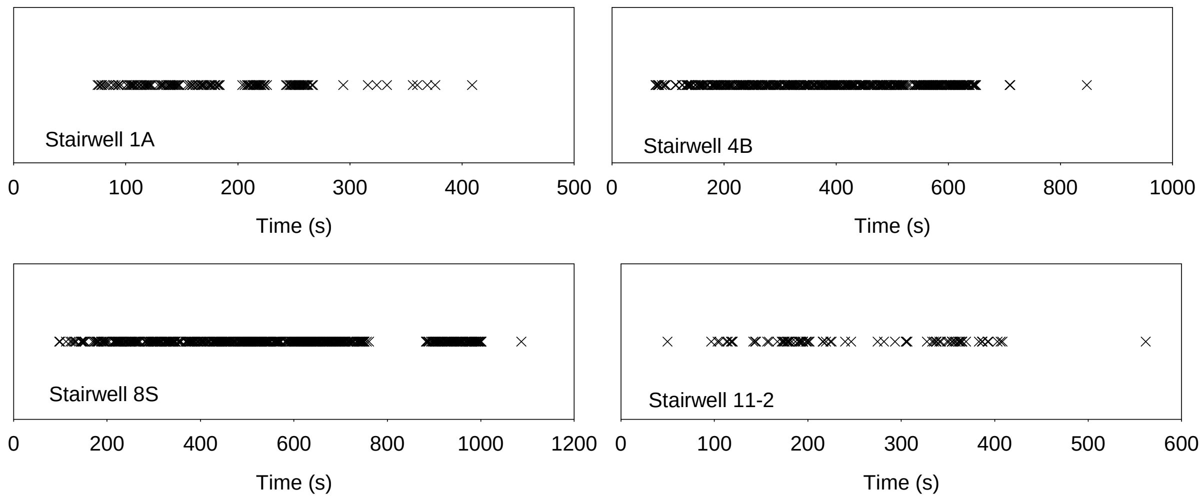


Figure E-1. Clustering of exit times for several sample stairs included in the study

The plots show clustering among the exit times due to occupant to occupant interaction. Therefore, a reasonable starting assumption is that the intensities of the pre-observation and travel times depend on the event histories of these processes. In a Hawkes model [91-93] this clustering is due to some self-exciting mechanism within a stair and among the occupants. In a self-exciting process, the occurrence of an event gives rise to subsequent events [92]. This is typical in building evacuations, where clusters are generated by seeds, as in an epidemic model, and from each seed, followers or offspring are generated to produce clusters. This model has been used previously for a range of applications such as modeling seismic data, stock, and commodity data.

The conditional intensity associated with the Hawkes model is given by

$$\lambda = \lambda_\theta\left(t \middle| \mathcal{H}_t\right) = \begin{cases} \mu + \alpha \sum_{t_i < t} e^{-\beta(t - t_i)} & \text{if } t > t_1 \\ \mu & \text{if } t \le t_1 \end{cases} \tag{6}$$

where μ is the background intensity and is the component of intensity absent human interaction, and $\mu + \alpha \sum_{t_i < t} e^{-\beta(t-t_i)}$ is the component of intensity representing human interaction. The parameter α can be interpreted as the strength that a cluster will form and the damping term β represents how fast clustering dies down with time.

For any point process with conditional intensity $\lambda_\theta\left(t \middle| \mathcal{H}_t\right)$, the joint probability of the event times $t_1, t_2, \ldots, t_n$ is

$$L(t_1,\ldots,t_n) = \rightarrow \prod_{i=1}^{n} \lambda\left(t_i \middle| \mathcal{H}_{t_i}\right) e^{-\int_0^{t} \lambda\left(u \middle| \mathcal{H}_u\right) du} \tag{7}$$

From this, the log-likelihood for the Hawkes model is

$$\log L\left(t_1,\ldots,t_n \middle| \mu,\alpha,\beta\right) = -\mu t_n + \sum_{i=1}^{n} \frac{\alpha}{\beta}\left(e^{-\beta(t_n-t_i)} - 1\right) + \sum_{i=1}^{n} \log\left(\mu + \alpha A_i\right) \tag{8}$$

where $A_i = \sum_{t_j < t_i} e^{-\beta\left(t_j - t_i\right)}$ for $i \geq 2$ and $A_1 = 0$. The maximum likelihood estimates are the value of μ, α, and β that maximize $\log L\left(t_1,\ldots,t_n \middle| \mu,\alpha,\beta\right)$.

It is of interest to quantify the accuracy of the maximum likelihood estimates. Let N(t) be a point process with bounded, strictly positive conditional intensity, $\lambda_\theta\left(t \middle| \mathcal{H}_t\right)$ and compensator $\Lambda_\theta(t) = \int_0^t \lambda_\theta\left(s \middle| \mathcal{H}_s\right) ds$. Then, under the time change $t \rightarrow \Lambda_\theta(t)$, the function $\tilde{N}(t) = N\left(\Lambda_\theta^{-1}(t)\right)$ is a unit rate Poisson process. Let τ_i be defined as $\tau_0 = \Lambda_\theta(t_1)$ and $\tau_i = \tau_{i-1} + \Lambda_\theta\left(t_{i-1}, t_i\right) = \Lambda_\theta\left(t_i\right) - \Lambda_\theta\left(t_{i-1}\right)$. The random variables $\tau_i - \tau_{i-1} = \Lambda_\theta\left(t_{i-1}, t_i\right)$ are exponentially distributed with a rate of 1. Quantile plots can be used to facilitate the residual analysis.

The above may be used to compute the probabilities $P\left[N(t) = k\right], k = 0,1,2,\ldots$. That is, the probability that k persons will exit in the time interval (0,t]. Recall that $N(t) = \#\left\{t_1 \leq t, t_2 \leq t, \ldots, t_n \leq t\right\}$. If the compensator is strictly increasing this is equivalent to $\#\left\{\Lambda(t_1) \leq \Lambda(t), \Lambda(t_2) \leq \Lambda(t), \ldots, \Lambda(t_n) \leq \Lambda(t)\right\}$. From the above,

$$P\left[N(t) = k \middle| \mathcal{H}_t\right] = \frac{e^{-\Lambda(t)} \Lambda(t)^k}{k!} \tag{9}$$

Integrating gives

$$P\left[N(t)=k\right]=\int_0^t \frac{e^{-s}s^k}{k!}\,dP\left[\Lambda(t)<s\right] \tag{10}$$

There is no closed form expression for $P\left[\Lambda(t)<s\right]$, but it can be estimated by simulation. There are numerous algorithms to simulate a Hawkes process.

Treating the stair flows as point processes also facilitates statistical analysis to allow determination of the relative contributions of significant engineering variables, e.g., stair width, tread depth, tread height, and other variables (see sections 4.5 and 4.6). Associated with each stair are three flow point processes: pre-observation time, travel time and total exit time; all are modeled as Hawkes processes with intensities

$$\lambda_j(t)=\hat{\mu}_j+\hat{\alpha}_j\sum_{t_i<t} e^{-\hat{\beta}_j(t-t_i)} \quad \text{if } t>t_1 \quad \lambda_j(t)=\hat{\mu}_j \quad \text{if } t\le t_1 \tag{11}$$

where $\hat{\mu}_j$, $\hat{\alpha}_j$, and $\hat{\beta}_j$ are maximum likelihood estimates. One can easily show that the intensity of the total time is a convolution of the intensities of the pre-observation time and the travel time intensities. A mean exit intensity for the *j*th stair can be derived for each stair by

$$m_j=\frac{1}{T_j}\int_0^{T_j}\lambda_j(s)ds \tag{12}$$

where T_j is the largest exit time for the *j*th stair. Each is an average intensity of all local intensities $\lambda(s), s\in\left[0,T_j\right]$ and can be thought of as an estimate of $E\left[\lambda(t)\middle|\mathcal{H}_t\right]$. The units of m_j are number of persons/sec and it can be shown

$$\frac{1}{T}\int_0^T \lambda(s)ds=\mu-\left(\frac{\alpha}{\beta}\right)\frac{1}{T}\sum_{i=1}^{n}\left(e^{-\beta(T-t_i)}-1\right) \tag{13}$$

Each m_j can be estimated by replacing the parameters μ, α and β by their maximum likelihood estimates.