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Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories

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ABSTRACT

The time that it takes an occupant population to reach safety when descending a stairwell during building evacuations is typically described by measurable engineering variables such as stairwell geometry, speed, density, and pre-evacuation 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 stairwell movement data during fire drill evacuations of office 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. To date, NIST has collected fire drill evacuation data in eight office building occupancies ranging from 6 to 62 stories in height that have included a range of stairwell widths and occupant densities.

While average movement speeds in the current study of 0.48 m/s ± 0.16 m/s are observed to be quite similar to the range of literature values, local movement speeds as occupants traverse down the stairwell are seen to vary widely within a given stairwell, ranging from 0.056 m/s to 1.7 m/s. These data should provide confirmation of the adequacy of existing literature values typically used for occupant movement speeds or provide updated values for future analyses.

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1. Introduction and background

Timing of occupant descent down stairwells during building evacuations is typically described by measurable engineering variables such as stairwell geometry, speed, density, and pre-evacuation 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. While there are dozens of models to simulate the evacuation of occupants from a given building geometry (Kuligowski et al., 2010), there is limited contemporary data to support the model inputs or assumptions and even less information available to validate the models for actual emergencies. While some models have had extensive validation efforts by the developers (Kuligowski et al., 2010) and others have included uncertainty in the analysis for a few limited data sets (Lord et al., 2005), there is still a significant need for independent data on evacuation behavior both for further development of the models as well as independent validation efforts. Collection and analysis of basic evacuation data would also provide a basis for building code requirements, the practice of egress system design, and ensure robustness for analysis of emerging issues.

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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 stairwell movement data during fire drill evacuations of office buildings. These data collections are intended to provide a better understanding of this principal building egress feature and develop a technical foundation for codes and standards requirements. To date, NIST has collected fire drill evacuation data in eight office building occupancies ranging from 6 to 62 stories in height that have included a range of stairwell widths and occupant densities.

This paper builds on a paper from an earlier conference (Peacock et al., 2010) to examine evacuee movement in four additional buildings, local movement speeds in addition to overall movement speeds, and a regression analysis an initial examination of underlying factors that may influence occupant evacuation.

There are many factors that influence the evacuation of building occupants. Gwynne et al. discusses these and organizes the factors that influence evacuation into the following categories (Gwynne et al., 1999):

- Configuration of the building/enclosure.
- Procedures within the enclosure.
- Environmental factors inside the structure.
- Behavior of the occupants.

Configuration of the building/enclosure involves what is traditionally covered by the codes and standards, such as building layouts, number of exits, exit widths, travel distances, etc. Gwynne proposes that occupants may often use these elements in ways not intended by the code or the building's original design because they may be unfamiliar with the building and be without staff guidance to aid in the evacuation. Another main issue that is frequently studied with building configuration is the way people move throughout the different components of the building, including both horizontal and vertical movement. Fruin (1987), Pauls (1995), Nelson and Mowrer (2002), and Proulx (2002) have studied this topic to understand movement through building components such as corridors, doorways, and stairways.

Proulx (2002) and others have studied the 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. In three office buildings, Proulx (2002) found an average delay of 50 s. Brennan reported delays averaging 150 s in a severe fire in a high rise office building (Brennan, 1998). Lord et al. (2005) reviews a number of sources on evacuation initiation delay. Values reported for office occupancies average 165 ± 71 s (uncertainty is expressed as standard deviation). The cue received had a significant impact on occupant's time to evacuate. With "poorly audible alarms," longer times to begin evacuation were noted compared to those buildings with "good audible alarms" (Proulx and Fahy, 1997), with "precise voice messages, delivered either in person or through a voice communication system prompting a fast response from occupants (Shields et al., 1998; Proulx and Sime, 1991).

Stairway geometry, another configuration aspect of the building, also affects movement of the occupants. Occupant speed is affected by the number of steps, the angle of the stairway, depth of the tread, height of the riser, and the presence and location of handrails (Gwynne et al., 1999). Overall stairwell effectiveness in building evacuation is impacted by a number of factors including the number and location of stairs in the buildings, the stair geometry, the number of occupants per floor, the number of occupants descending from above a given location, any obstacles the occupants may encounter during descent (such as fire responder counterflow or evacuating occupants who may become obstacles due to resting or injury, though not considered in this paper), and merging behavior as occupants enter the stairwell encounter descending occupants from higher floors.

While the exact manner in which merging behavior occurs may not be well understood (Galea et al., 2008), a number of studies have observed general trends in stairwell merging. Different types of merging are possible. Occupants in the stairs may defer to occupants entering the stairs (Pauls and Jones, 1980; Proulx et al., 1996; Shields et al., 2009). Occupants on the floors may defer to those already in the stair (Hostikka et al., 2007). Finally, neither may defer and the occupants on the floor and those already in the stair split evenly. Kagawa et al. (1985) 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. (2011) report that preference split between the stairs and floor, but the ratio depended on the speed and geometry. As occupants merged into the stair, the flow could slow down or become stagnant (Proulx et al., 2007). Clearly merging behavior can impact stair movement. While not studied for this paper, additional analysis of videos collected for this study could provide additional data on these deference behaviors.

Proulx (2002) 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), and the mobility of the person traveling either up or down a flight of stairs.

Literature values are available for movement down stairwells. Proulx (2002) and Lord et al., 2005) reviewed data on occupant speed, flow, and density. The range of values for occupant speed is shown in reference (Peacock et al., 2010). For occupants with mobility impairments, the literature ranges from 0.16 m/s to 0.76 m/s; for studies with no reported impairments, 0.17 m/s to 1.9 m/s (not including Fruin's "crush load" value). These data are summarized in Table 1, updated from reference (Peacock et al., 2010).

2. Data collection for buildings included in current study

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 earlier, is that fire drill data can be used to approximate the response of individuals in an actual emergency (Proulx, 2002). 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 conceivable that a significant portion of the population has not been exposed to enough fire cues to be certain if it is an emergency. Information from real emergencies can inform fire drill data collections and provide a check of the validity of fire drill data.

2.1. Data collection procedures

In this study, fire drill evacuation 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 the evacuation. In most buildings, unless specified, the video cameras were placed on every other floor to capture a view of that floor's main landing, the door into the stair at that level, and 2–3 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.

After video data was taken from each building evacuation drill, 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. 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,
- the time that he/she was seen leaving the camera view (see Fig. 1),
- his/her location on the stair (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), and
- his/her handrail usage (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

Table 1
Occupant movement speeds in stairwells (updated from Peacock et al. (2010)).

Year	Movement speed (m/s)	Notes	Source
	0.52 ± 0.24	18–29 year old	Various [a,b], from Lord et al. (2005)
	0.52 ± 0.23	30–50 year old	Various [b], from Lord et al. (2005)
	0.49 ± 0.18	>50 year old	Various [b], from Lord et. al. Lord et al. (2005)
	0.16–0.76	Disabled occupant	Various, from Lord et al. (2005)
1969	0.58 ± 0.15		Predtechenskii and Milinskii (1978)[c]
1972	0.762	Maximum	Fruin (1987), from Pauls (1995)
1972	0.6096	Moderate	Fruin (1987), from Pauls (1995)
1972	0.4826	Optimum	Fruin (1987), from Pauls (1995)
1972	0.2032	Crush	Fruin (1987), from Pauls (1995)
1988	0.33 ± 0.16	Locomotion disability	Boyce et al. (1999)
1988	0.7 ± 0.26		Boyce et al. (1999)
1995	1.1	Relatively fit	Proulx (2002)
	0.5		Proulx (2002)
2001	0.2	Median value, 9/11 WTC Towers	Averill et al. (2005)
2001	0.26	WTC North Tower	Galea et al. (2010)
2004	0.76–1.3	Varied walking angle	Fujiyama and Tyler, 2004 adapted by Hostikka et al. (2007)[d]
2005	0.83 ± 0.18	6-Story	Peacock et al. (2010)
2005	0.62 ± 0.10	11-Story	Peacock et al. (2010)
2005	0.40 ± 0.18	18-Story	Peacock et al. (2010)
2006	0.14–1.87	Photoluminescent stairwell markings	Proulx et al., (2007) and Proulx and Bénichou (2010)
2007	0.64		Hostikka et al. (2007)

[a] Includes data from Fruin (1987), Predtechenskii and Milinskii (1978), Boyce et al. (1999), Proulx (1999), Proulx et al. (1995), Fahy and Proulx (2001), Wright et al. (2001).
[b] Largely data from office occupancies, but also include data from Proulx (1999) on residential evacuations.
[c] Includes movement speeds for densities the authors define as typical for stairwell evacuation.
[d] Data converted from horizontal speed to speed along incline with given stair geometry.

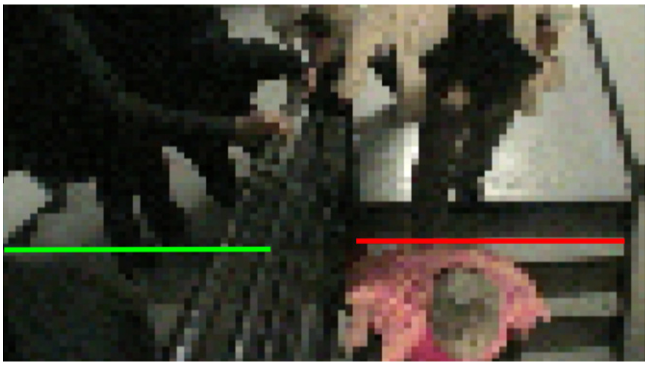

Fig. 1. Data collection points for evacuees entering and leaving camera view from an overhead camera video recorded during a fire-drill evacuation. Pixelation is as originally recorded on the camera.

exit lane variable, this variable could change for a given occupant at subsequent floors and was only available when visible in a camera view on landings and several steps above or below the landings).

The data collected for each occupant (overall) during the evacuation drill were the following information:

- gender (Occupants were classified as being female, male, or unknown),
- floor of origin/travel distance (recorded as the number of floors since the occupant was first seen on the camera.),
- whether he/she was carrying anything (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 (less then ½ the stair width or more than ½ the stair width),
- whether he/she was alone or in a group during the drill, and
- whether he/she was helping someone during the drill.

This paper focuses on four evacuations in buildings ranging from 10 to 31 stories and builds on a previous paper (Peacock et al., 2010). All of the buildings were typical office occupancies in the United States with from 197 to 704 total evacuees in an individual stairwell. These data are available on the NIST website at http://fire.nist.gov/egress/. A brief description of each building evacuation is included below.

2.2. 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 exit stairs; Stairs A and B, both of which exit directly out of the building on the first (or ground) floor. The two exit stairs are 1.27 m (50 in.) wide (1.22 m (48 in.) between handrails) and the individual steps measure 0.18 m (7 in.) rise and 0.28 m (11 in.) tread depth.

In Stairs A and B, from floors 10 to 2, there are 22 steps between floors (interrupted by a mid landing 11 steps between floors). From floor 2 to 1 in Stairs A and B, there are 27 steps in between floor 2 and 1 (13 steps from floor 2 to the mid landing and then another 14 steps from the mid landing to the exit floor).

The evacuation drill took place in the spring months of 2008 during normal business house (before lunch). 804 occupants participated in the unannounced full building evacuation drill (436 in Stair A and 368 in Stair B). During the drill, six firefighters traveled up Stair B to the 7th floor approximately 8–11 min into the evacuation drill; i.e., when the drill was almost completed but consistent with typical fire department response times. Also during the drill, additional fire fighters assigned to specific floors began floor searches to ensure that all occupants evacuated as soon as the alarm sounded.

2.3. 18-Story office building

This building 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 12 exit stairs available for egress, numbered one through twelve. Data were collected in four of these exit stairs from different wings throughout the building. All four exit stairs were 1.12 m (44 in.) wide (0.91 m (36 in.) between handrails) and the individual steps measure 0.19 m (7.5 in.) rise and 0.25 m (10 in.) tread depth. Stairs 3, 7, and 12 exited to the lobby area on the fifth floor (ground level in the front of the building) each through a 0.91 m (36 in.) wide doors; while Stair 1 continued to the first floor and exited directly out of the rear of the building.

In Stair 1, there are 16 steps between floors (interrupted by a mid landing 8 steps between floors) from floors 18 to 4, and floors

3 to 2. In between floors 4 and 3 and 2 and 1, there are 18 steps between floors (interrupted by a mid landing 9 steps between floors). In Stairs 3, 7, and 12, there are 16 steps between floors (interrupted by a mid landing 8 steps between floors) from floors 18 to 6, and then a total of 19 steps in between floors 5 and 6 (9 steps to the mid landing and then 10 steps to the main landing/exit on floor 5).

In the building'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 accidental alarm that initiated a building evacuation and one small fire that also initiated a building evacuation without injury to the occupants.

The evacuation drill took place in the spring months of 2008 during normal business hours (before lunch). Within the four exit stairs observed, 1084 occupants participated in the unannounced full building evacuation drill (255 in Stair 1, 292 in Stair 3, 340 in Stair 7, and 197 in Stair 12). During the drill, a total of 17 firefighters traveled up Stair 12 from the 5th floor to the 12th floor; one group of seven fire fighters 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 exit stairs near Stair 2–Stairs 1 and 3 – than normally expected during an evacuation).

On the day of the drill, data were collected from 30 different camera locations in the four exit stairs observed. In Stairs 3, 7, and 12, seven 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. For the 18-story building, the times of the occupants entering the camera view are taken two steps away from the main landing (leading to the main landing) and three exit stairs away from the main landing (leading away from the main landing).

2.4. 24-Story office building

The occupants in this building perform yearly staged evacuation drills (drills where occupants descend two floors by stairwell but do not fully evacuate the building); however, they participate in a full-building evacuation drill every 5 years. On a typical day, the building houses a population of approximately 1500 people. The building has two exit stairs; Stairs A and B. Stair A exits onto the 2nd floor lobby where occupants must travel through the lobby to exit the front of the building at ground level. Stair B, on the other hand, exits directly to the outside on Floor 1. Both exit stairs are 1.12 m (44 in.) wide (1.02 m (40 in.) between handrails) and the individual steps measure 0.18 m (7 in.) rise and 0.28 m (11 in.) tread depth.

In Stairs A and B, from floors 24 to 3, there are 20 steps between floors (interrupted by a mid landing 10 steps between floors). In Stair A between floors 3 and 2 (the exit floor), there are 30 steps between these floors (interrupted by two mid landings with 10 steps on either side of the landings). In Stair B in between floors 3 and 1 (the exit floor), there are 60 steps between these floors (interrupted by five mid landings with 10 steps on either side of the landings).

The evacuation drill took place in the spring months of 2008 during normal business hours (before lunch). 605 occupants participated in the unannounced full building evacuation drill (249 in Stair A and 356 in Stair B). During the drill, three firefighters traveled up Stair A to the 13th floor approximately 1.5 min into the evacuation drill. Also during the drill, additional fire fighters assigned to specific floors began floor searches to ensure that all occupants evacuated as soon as the alarm sounded.

2.5. 31-Story Office Building

On a typical day, the building houses a population of approximately 2100 people. The building has two exit stairs (North and South) that both exit on the 2nd floor onto the street level. The two exit stairs are 1.38 m (54.25 in.) wide (1.26 m (49.75 in.) between handrails) and the individual steps measure 0.18 m (7 in.) rise and 0.27 m (10.75 in.) tread depth.

The travel distances between floors vary throughout the building. From floors 31 to 4, there are 18 steps between floors (interrupted by a mid landing 9 steps between floors). Between floors 3 and 4, the stair configuration introduces a horizontal transfer corridor around the mechanical area, essentially adding an additional floor between floors 3 and 4. For that reason, the travel distances between floors 3 and 4 are larger. From floors 3 to 2, there are 27 steps (interrupted by two mid landings with nine steps between each landing). Finally, there is a horizontal travel distance from the North stair to the exit of the building.

The evacuation drill took place in the fall months of 2008 during normal business hours (before lunch). Occupants did not have prior notification that a drill was planned. Additionally, the elevators were not available for the general 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, guided and aided by building emergency staff. Overall, 1242 of building occupants participated in this evacuation drill (704 in the North Stair and 538 in the South stair).

Data were collected data from 30 different camera locations in the two exit stairs observed. In both exit stairs, Cameras were placed every other floor, specifically on floors 30–14 (every other floor), 11, 9, 7, 5, 4, and 2. Cameras were placed on odd floors between floors 11 and 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 the exit floor (floor 2) must be equipped with a camera to obtain exit times for all participants.

3. Overall movement speed

A summary of the four buildings included in the current study along with the total number of evacuees and overall evacuation time for each of the buildings is shown in Table 2. Calculation of pre-observation delay, travel speeds and stairwell densities were determined from the video timing data as follows:

- Pre-observation delay was defined for each occupant as the time from initial alarm until the occupant was seen entering the stairwell to evacuate the building. Occupants who entered the stairwell between camera locations were not included in calculated average values since they had to descend at least one floor in the stairwell prior to entering a camera view. In general, this is expected to be a longer time than the typical pre-evacuation delay time since it includes time for movement to the stairwell in addition to the time for any activities prior to initiation of movement towards the exit stairwell.
- Fig. 2 illustrates calculation of travel distance. Distance along the stair treads was determined as the diagonal distance down the stairs and landings were determined consistent with Predtechenskii and Milinskii (1978) where occupants were assumed to travel down the center of the stairs and around landings maintaining similar spacing from the inside of the landings.
- Local travel speeds were calculated using the distance and time between camera positions (usually every two floors) for each occupant (While it was possible to calculate travel speeds on single landings, in practice, travel times on an individual landing were short enough to lead to excessive uncertainty). Overall travel speed was calculated using the time each occupant

Table 2
Stairwell geometry and evacuation details for buildings included in the current study.

	10-Story building	18-Story building	24-Story building	31-Story building
Occupancy	Office	Office	Office	Office
Floors	10	18	24	31
Stair width[a] (m)	1.27	1.12	1.12	1.38
Stair riser (mm)	178	191	178	178
Stair tread (mm)	279	254	279	273
Exit width (m)	0.91	0.83	0.91	0.91
Evacuees (for each exit stair)	436/368	255/292/340/197	249/356	704/538
Evacuation time (s)	1022	1192	1090	1002

[a] Full stair width including handrails.

initially entered a camera view until they exited the view of the last camera prior to exiting the building. Distance along stair treads was taken to be along the slope of the stair treads.

- Local density was estimated as each evacuee entered the viewing area at each camera location from the number of persons in the camera view at that instant of time and dividing by the total area of the respective camera view. Fig. 2 illustrates the area calculation. No attempt was made to estimate density on stairs outside of the camera views though at higher densities, backups on the stairs were obvious from the videos.
- A summary of pre-observation times and average stairwell descent speeds is shown in Table 3. The average evacuee speeds in all stairwells of the buildings are within experimental variability (as expressed by one standard deviation). Fig. 3 shows average local movement speeds for the four fire drills, including data from the drills included in an earlier paper (Peacock et al., 2010).

Fig. 3 also compares the current study to historical data. It is important to recognize that all of these data were collected under differing conditions, with a range of building heights (ranging from a few stories to about 30 stories in height), occupant capabilities (one study looked specifically at occupants with locomotion disabilities), and evacuation conditions (many were fire drills, but actual events are also included). With the considerable variation in all the available data (as indicated by the standard deviation shown for many 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 (1987).

Average movement speeds in the literature for very dense evacuations (Fruin's crush load Fruin, 1987 and the 9/11 World Trade Center evacuation (Averill et al., 2005; Galea et al., 2010) are significantly lower than both the current study and average values from the literature. This may be indicative of the difference between fire drill evacuations and real emergency situations or due to higher occupant densities in the slower stairwells.

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

The distribution of stairwell movement speeds in the buildings shown in Fig. 4a and the cumulative distribution functions shown in Fig. 4b provide additional details of the range of speeds in the evacuations. Overall, 19% of the occupants move slower than 0.4 m/s (63% of these are in the 18 story building; 99% of these are in the 10-, 18-, and 31-story buildings) and just 2% move faster than 1 m/s. With the exception of the 6-story building (data from the earlier paper (Peacock et al., 2010), the cumulative probability curves show similar shapes with the majority of speeds between 0.3 m/s and 0.7 m/s. The 6-story building tends towards faster movement speed, consistent with the higher overall average movement speed of 0.78 m/s ± 0.23 m/s compared to an average of 0.52 m/s ± 0.19 m/s for all of the buildings examined.

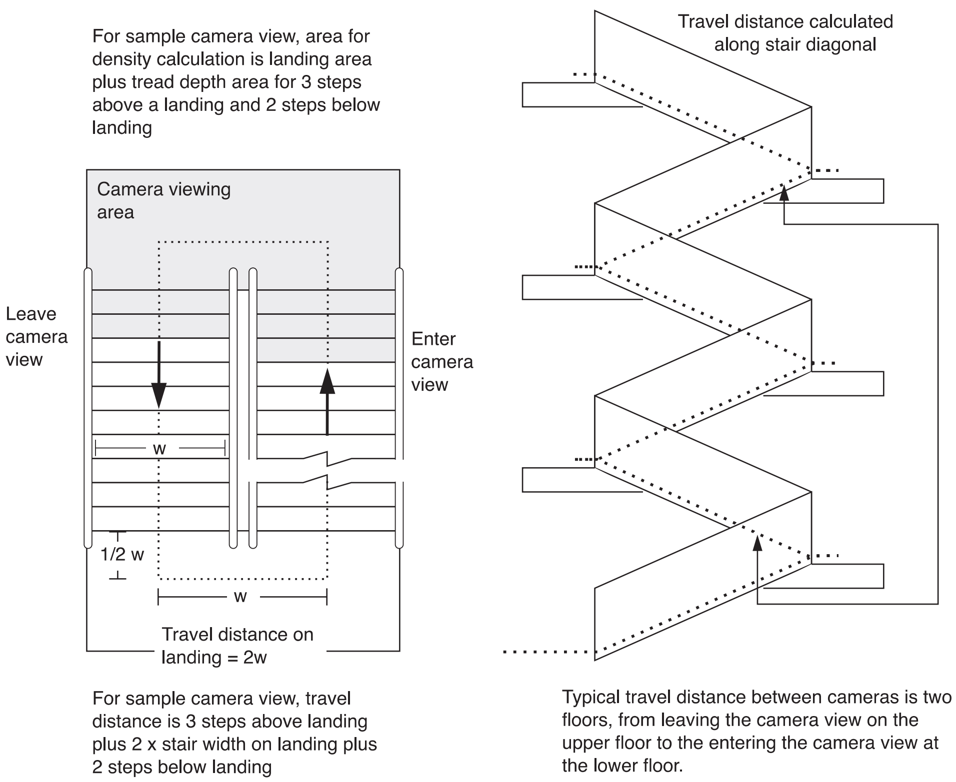

Fig. 2. Travel distances and area calculations for stairwell evacuations.

Table 3
Pre-observation time and stairwell movement speeds in several fire drill evacuations.

Building	Evacuees[a]	Average pre-observation delay time[c] (s)	Average speed[c] (m/s)
6-Story[b]	273	142 ± 60	0.78 ± 0.23
10-Story	793	171 ± 124	0.44 ± 0.19
11-Story[b]	127	89 ± 54	0.62 ± 0.26
13-Story[b]	226	106 ± 50	0.69 ± 0.09
18-Story	1148	224 ± 146	0.44 ± 0.15
24-Story	593	137 ± 86	0.56 ± 0.12
31-Story	525	149 ± 88	0.52 ± 0.10

[a] Does not include evacuees who did not exit at the lowest camera location.
[b] Data from earlier study (Peacock et al., 2010).
[c] Uncertainty is expressed as one standard deviation.

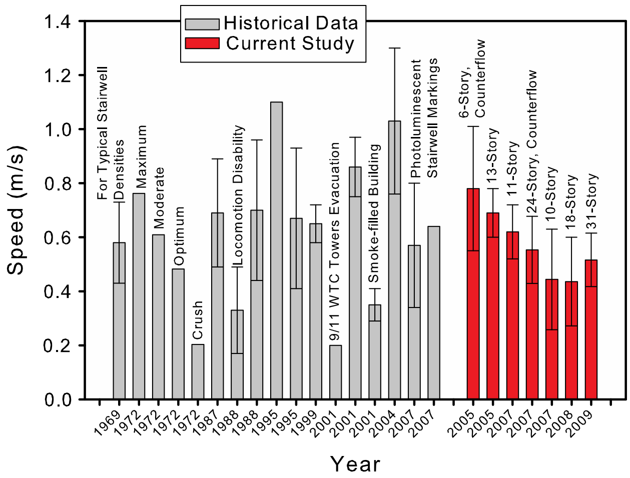

Fig. 3. Comparison of current study average stairwell descent speeds with literature values. Where available, data points include standard deviation of average movement speeds.

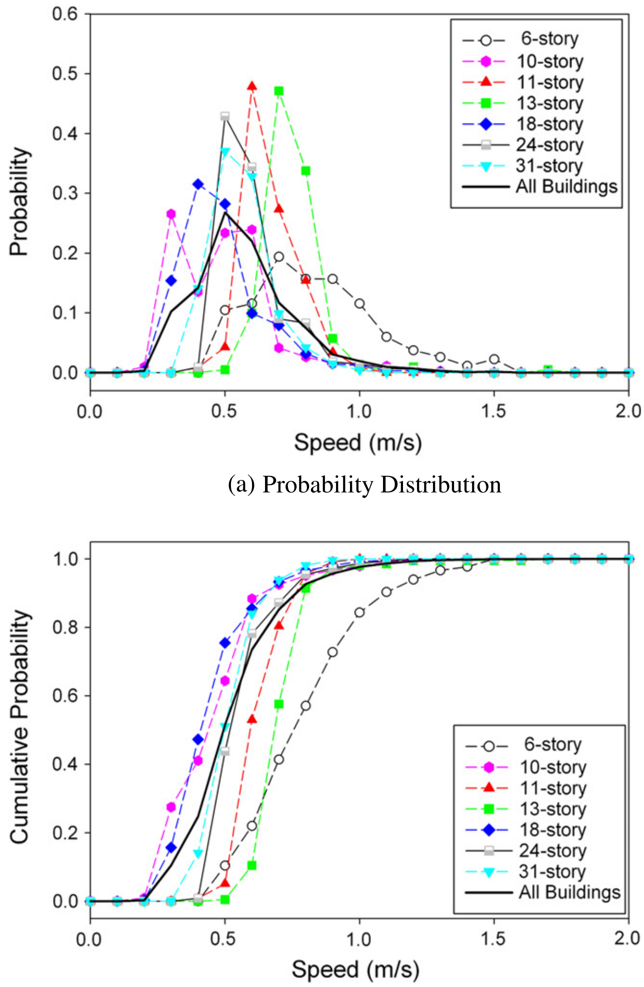

Fig. 4. Distribution of movement speeds down stairwells in several fire drill evacuations.

4. Local movement speeds

Fig. 5 shows an example of the movement for each individual in one of the stairwells in the current study (simply an arbitrary choice of the south stairwell of the 31-story building). There is a wide range of the time that evacuees arrive at the stairwell to begin their stairwell evacuation (ranging from 30 s to 590 s relative to fire alarm activation) and of total evacuation time (ranging from 97 to 1002 s relative to fire alarm activation). In addition, individual movement speeds, indicated by the slope of each curve, routinely varies as an evacuee travels down the stairwell. Overall movement speed, arguably the most commonly reported value for evacuee movement in stairwell evacuation thus illustrates only a small part of the dynamics of movement during an evacuation. Though not surprising, there is considerable variation in movement speed not only among individuals involved in the evacuation, but also for each individual as they proceed down the stairwell during the evacuation.

Fig. 6 shows the variation in local movement speeds (here an average speed for all evacuees passing each camera location). The average local movement speed varied by floor within a building. Fastest speeds are seen lower in the building, slower speeds on the middle floors, and typically somewhat faster speeds high in the building, but not to the levels seen lower in the building. While there were also differences between buildings, these are largely within the standards deviation for a floor and dwarfed by the range of local speeds as shown in Fig. 7. Individual local speed ranged from 0.06 m/s to 1.2 m/s (though with a single individual starting the evacuation with a local speed of 1.7 m/s on the top floors of the 31-story building). A wide range in local speeds was evident on all floors, stairwells, and buildings studied.

Some of the variation in local speed is attributable to changing evacuee density as the evacuation proceeds. Fig. 2 shows a schematic of the calculation within each stairwell. As an example, Fig. 8 shows the evacuee density as a function of time in the four monitored stairwells in the 18-story building. As the evacuation progresses, multiple floors of each stairwell became quite crowded. Not surprisingly, densities high in the building were the lowest as there were fewer total occupants at or above a given floor higher in the building. A notable limitation to the density calculations in this study is that they are based on density within the viewable area at each camera location. Primarily, this includes the stairwell landings and only a few stairs on either side of the landing. Actual densities in the stairwells and landings outside of camera views were not estimated.

Fig. 9 shows local speed as a function of density for evacuees in the 24-, 10-, 18-, and 31-story buildings. Each data point in the figure was calculated as follows: As each evacuee entered a camera view at a given floor, their individual speed and density were calculated as described above (speed was based on the travel distance and time between this and the successive camera location and density was based on the number of evacuees on the current landing as the evacuee entered the camera view). Each data point is then a 60 s average of all evacuees passing a given camera location

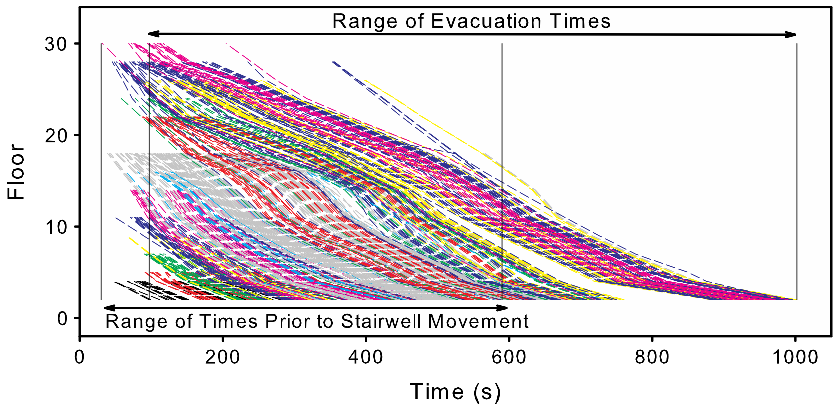

Fig. 5. Timing of movement for 475 evacuees during a fire drill evacuation of a 31-story office building.

in a given building. Thus, there may be multiple data points for a given floor (since evacuation of a floor occurs over a period of time that may exceed the 60 s averaging time) and for a given occupant (that may be represented in more than one time average as they descend from floor to floor down a stairwell).

Also shown in the figure is the correlation for evacuation speed as a function of density from the SFPE Handbook of Fire Protection Engineering Proulx (2002) based on the data of Fruin (1987), Pauls (1980), and Predtechenskii and Milinskii (1978). While the correlation is contained within the data from the current study and the evident decrease in speed with increasing density is understandable, the fit of the correlation to the data (with an R^2 of about 0.2) again highlights the inherent variability in the data and indicates that density is certainly not the only variable the impacts the movement speed of evacuees. There are several contributors to this uncertainty. Since observations are only available on or near floor landings, speed and density could be and likely was different on the stairwells between camera views. Refinements in the methods used to calculate the areas used to calculate density that better accounts for the area actually occupied by evacuees could also lead to better results. Finally, a more detailed analysis of individual movement speeds from these data indicates that speed is largely controlled by the first persons in a group traveling down the stairs. When the evacuees are divided into these flow unit groups, the inclusion of their interactions with other flow units (the actions of the first persons relative to the other flow units and the flow type), as well as characteristics of the first person in the flow unit (most of which are included in the regression models in this paper), leads to much stronger correlations (Hoskins, 2011).

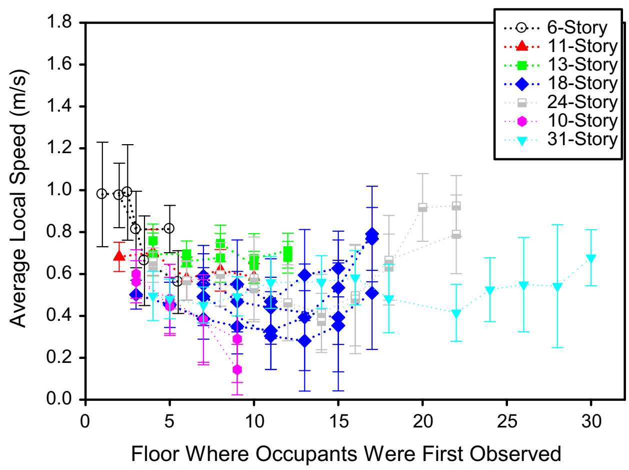

Fig. 6. Occupant movement speed (with standard deviation) down stairwells in several fire drill evacuations.

5. Regression modeling

To investigate the underlying causes for differences in movement speeds, a regression model was constructed to explore the components affecting occupant descent speeds in the stairwells for the 10-, 18-, 24-, and 31-story buildings. These included the typical engineering parameters that can be directly measured during the evacuation. The dependent variable, local movement speed, was calculated based on the time difference between when the occupant was seen on adjacent camera positions (typically two floors apart in a stairwell and the known distance between the two cameras. A total of eight independent variables were included in the model to predict the local movement speed. These variables were: stairwell number, gender, carrying objects, exit lane, handrail use, pre-observation time, density, and travel distance. The first five variables were categorical variables where each data point belonged to one level of each variable. The final three variables were continuous variables where the value for each data point could fall along a continuum.

SPSS Version 12.0.1[1] was used to estimate the linear regression model gauging the net effects of the independent variables on the local movement speed (Table 4). The correlation was significant at the less than 0.001 level. For the categorical variables, reference values were chosen simply to allow comparison. The selected reference values were as follows: male, not carrying anything, middle exit lane, not using the handrail, and the 31-story building stairwell. Table 4 includes the unstandardized and standardized coefficients for each variable as well as the standard error and significance for all the variables in the main effects model. For the categorical variables, the coefficients are interpreted as the increase in local movement speed for someone with that characteristic compared to someone with the reference characteristic independent of all other variables. For the continuous variables, the coefficients are interpreted as the increase in speed when the independent variable increases by one unit and all other variables are held constant.

The data was examined to ensure that the assumptions of regression modeling were met. To ensure that there was no multicollinearity (two or more independent variables being highly correlated), zero-order correlation matrices were examined and no

[1] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

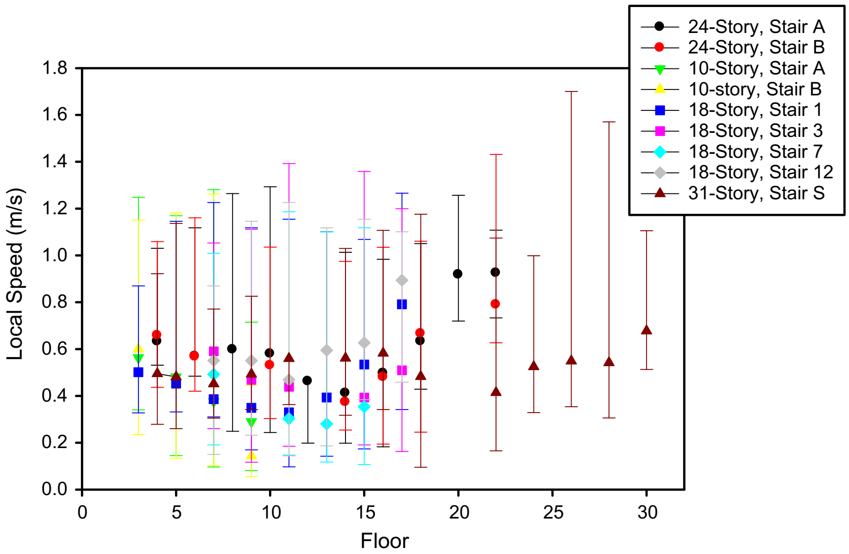

Fig. 7. Range of local movement speeds on each floor during several fire drill evacuations.

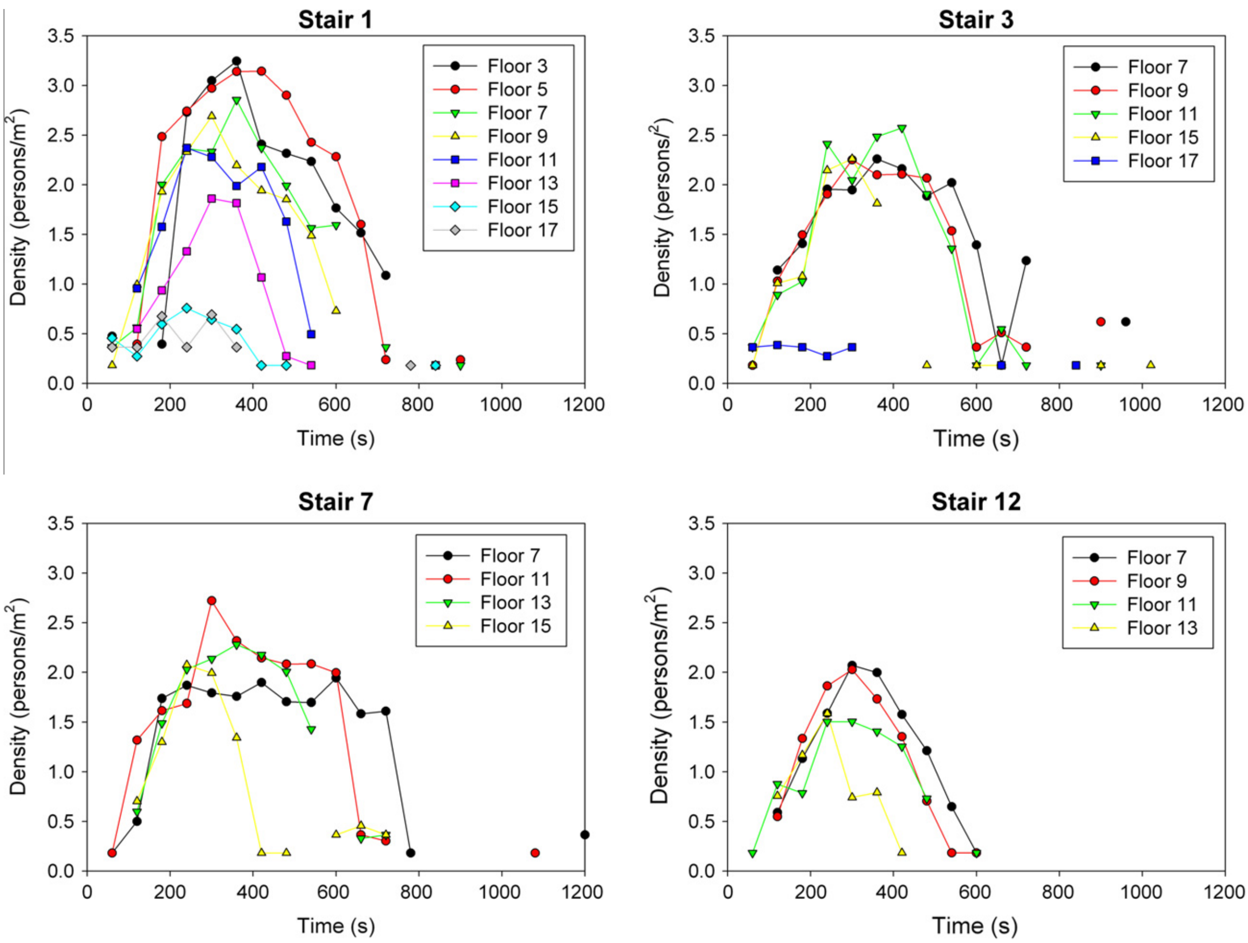

Fig. 8. Evacuee density (people/m^2) as a function of time in four stairwells during a fire drill evacuation in an 18-story building.

multicollinearity was detected. Heteroscedasticity was tested by graphing the residuals versus the independent variables. Two of the variables, density and pre-observation time, failed the test. While the coefficients are still accurate based on the assumptions of regression modeling, the standard deviations, and thus the significance, might not be. The coefficient for pre-observation time was found to be significant, but relatively small. Thus, treating it as if it was not significant leaves the findings unchanged. For density, the model was run again by changing the density variable to a categorical variable based on Fruin's Level of Service (Fruin,

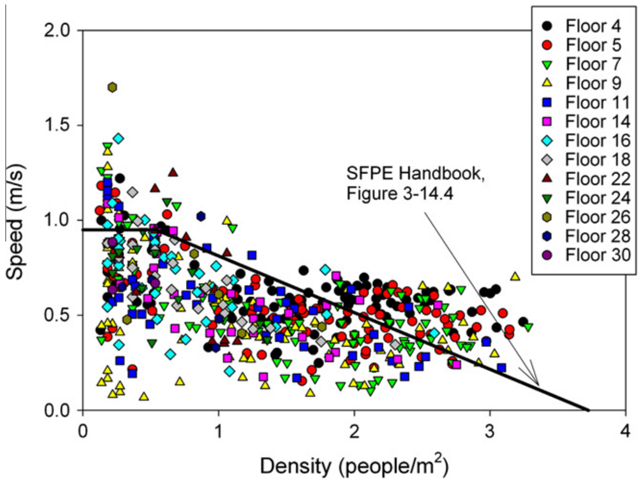

Fig. 9. Local speed as a function of local density for evacuees in all stairwells of 10-, 18-, 24-, and 31-story buildings during fire drill evacuations.

Table 4
Main effects regression model for local movement speed.

Model	Unstandardized coefficients		Standardized coefficients	
	B	Std. error	Beta	Significance
(Constant)	.625	.007		.000
Density	−.082	.002	−.376	.000
Women	−.010	.003	−.029	.003
Carry	−.010	.004	−.027	.006
Travel distance	.000	.000	−.012	.219
Pre-observation time	8.3×10^{-05}	.000	.053	.000
Inner exit lane	−.007	.005	−.017	.189
Outer exit lane	−.009	.004	−.024	.054
Handrail	−.002	.004	−.007	.514
Stair 4A	.143	.006	.258	.000
Stair 4B	.131	.006	.223	.000
Stair 5A	.028	.007	.043	.000
Stair 5B	.014	.007	.021	.039
Stair 7-1	−.025	.006	−.046	.000
Stair 7-3	.011	.007	.016	.120
Stair 7-7	−.107	.008	−.137	.000
Stair 7-12	.044	.007	.059	.000

1987). All levels were found to be significantly different from 0 at the <0.001 level, so the density variable is significant in this model.

Of the eight variables in the regression model, six were significant at the 0.10 level or lower. The final regression model explained 21% of the variance in the local movement speeds included in this study.

As expected, the regression analysis shows that as density increases, speed decreases. Individuals traveling in more dense situations were not able to move as fast as individuals in less dense situations. This matches the plots of the data shown previously (see Fig. 9) as well as the previously cited studies.

Individuals carrying anything were slower than those who were not. Evacuees traveling near the inner and outer edges of the stairwells travelled slower than those in the middle. Men travelled at speeds slightly faster than women. Movement speed from one stairwell to another was found to be different by up to 0.27 m/s. This implies that some variable(s) not included in this model causes occupants to move at different speeds.

The change in local movement speed based on travel distance was not significant and, for pre-observation time, the change was significant but relatively small for most occupants; the heteroscedasicity also could make this value insignificant, so no findings should be drawn from it.

Secondary interaction terms between the different variables were examined to see if combinations of variable levels were behaving differently than other types. Two general trends in the interactions were noted. The first set of trends involved interactions with density. The second set involved interactions with the different stairwells.

As density increased, all of the variation in other variables tended to approach zero. In essence, for a highly dense flow, the speed of all occupants was more similar than in the lighter density situation. In the main effects model, this difference will cause several of the terms to appear less significant than they are in reality. For example, using a handrail while in high density might not cause a difference in speed compared to other individuals in high density, but it does make a difference in lower density situations. The main effects model is unable to capture this distinction. Based on these interactions with density, future research should look at how the interactions between people within the group alter the individual movement speeds.

While stairwells within a building were generally similar, differences between buildings (and in the 19-story building, between individual stairwells) were substantial. For example, women moved faster than men in one of the buildings. Also, travel distance was significant in decreasing local movement speed in some of the stairwells while not being significant in others. Furthermore, individual characteristics like whether carrying an object, exit lane, and handrail use varied in how significant they were in influencing local movement speeds. In one building, the speed based on the density was significantly different than the other buildings. As was the case with density, these differences across buildings lead to the coefficients in the main effect model to appear less significant than they might be in reality.

Several assumptions made for data analysis will limit the accuracy of the data. While the density could be changing throughout the time interval of the movement speed calculation, the density at the start of the interval is assumed to be the value throughout. Also, the measurements for travel distance and pre-observation time for individuals that did not enter on a floor with a camera are off by the time and distance travelled until the first camera. For the model itself, the regression model is based on the linear estimators that best fit the data; excluded variables that could be significant in determining movement speed will not be captured and could be the cause of the differences between stairwells. In the main effects model, differences that were occurring based on different conditions (for example, at different densities) were not captured. Also, this model did not capture interactions with other occupants.

Overall, local movement speed could be predicted based on the eight variables used in this analysis. The speed depends on the characteristics of the occupants as well as the physical conditions within the stairs. There were also differences between speeds that were found to occur based on which building was being studied. Due to the similarities between these buildings, the exact cause of this difference is unknown.

6. Conclusions

This paper has summarized the typical engineering variables used to describe stairwell movement during building evacuations, reviewed literature values for movement speeds, and presented data from several new fire drill evacuations.

The following conclusions are evident from the study:

- Mean movement speed for the four buildings evacuations studied was 0.48 m/s ± 0.16 m/s.

- There is considerable variation in local movement speeds. Individual local movement speeds ranged from 0.056 m/s to 1.7 m/s. Using a distribution of movement speeds rather than a single value should provide more realistic representation of movement speed in stairwells.
- Data from the current study are reasonably consistent with historical data. Use of historical data may still be appropriate with the scope and limitations of the original collection.
- From the regression model, the two most significant variables were the stairwell that the occupant was in and the density. It is believed that the difference between stairwells comes from variables that were not included in this model. A clear relationship is evident in the data and regression analysis between density and speed. Algebraic formulas for prediction of speed as a function of density are a significant oversimplification of the process.
- This paper provides just a beginning in understanding the additional human behavior-related factors that impact movement beyond classic hydraulic calculation-based variables. Additional research is appropriate to better understand these factors.
- Data presented in this paper are available for review and/or further analysis at the NIST website, http://fire.nist.gov/egress.

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