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Summary. Occupant descent down stairwells during building evacuations is typically described by measureable engineering variables such as stairwell geometry, speed, density, and pre-evacuation delay. In turn, predictive models of building evacuation use these variables to predict the performance of egress systems for building design, emergency planning, or event reconstruction. This paper provides a summary of literature values for movement speeds and compares these to several new fire drill evacuations. Movement speeds in the current study are observed to be quite similar to the range of literature values. Perhaps most importantly though, the typical engineering parameters are seen to explain only a small fraction of the observed variance in occupant movement speeds. This suggests that traditional measures form an incomplete theory of people movement in stairs. Additional research to better understand the physiological and behavioural aspects of the evacuation process and the difference between fire drill evacuations and real fire emergencies are needed.

1 Introduction

Both before and since the World Trade Center tower collapses, there have been numerous events where there was extensive life loss because there was insufficient time for safe evacuation from a threatened building. While much attention has been focused upon the more readily quantifiable input parameters to fire models such as material flammability properties, little effort has focused on the need for a more fundamental understanding of occupant egress. High-profile scenarios such as the World Trade Center collapse routinely lead to public expressions requiring changes to the status quo regarding public safety. While there are dozens of models to simulate the evacuation of occupants from a given building geometry [1], there is limited contemporary data to support the model inputs or assumptions and even less information available to validate the models for actual emergencies. Collection and analysis of basic evacuation data would provide a basis for building code requirements, the practice of egress system design, and ensure robustness for analysis of emerging issues. While some models have had extensive validation efforts by the developers [2, 3] and others have included uncertainty in the analysis for a few limited data sets [4], there is still a significant need for independent data on evacuation behaviour both for further development of the models as well as independent validation efforts.

As a start to provide such data, this paper provides a review of published data for movement speeds on egress stairwells, and an analysis of three recent data sets involving full-building evacuation.

2 Occupant Movement in Building Evacuation

There are many factors and influences that play a role in the evacuation of building occupants. Gwynne discusses these in his article entitled "A Review of the Methodologies Used in the Computer Simulation of Evacuation from the Built Environment" [5] and organizes the factors that influence evacuation into the following categories:

- 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 can commit behavioral violations to this factor in a number of ways, for instance exit misuse, 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 [6], Nelson and Mowrer [7], Pauls [8], and Proulx [9] have studied this topic to understand movement through building components such as corridors, doorways, and stairways.

Proulx [9] 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 [9] found an average delay of 50 s. Brennan reported delays averaging 150 s in a severe fire in a high rise office building [10]. Lord, et. al. [4] reviews a number of sources on evacuation initiation delay. Values reported for office occupancies average 165 s $\pm$ 71 s (uncertainty is expressed as standard deviation).

Stairway geometry, another configuration aspect of the building, also affects movement of the occupants. 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, and any obstacles the occupants may encounter during descent (such as fire responder counterflow). 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 [5]. Proulx [9] found stairway movement involves a complex set of behaviours, 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 travelling either up or down a flight of stairs. People sometimes become obstacles in the evacuation process, due to exhaustion or injury.

Literature values are available for movement down stairwells. Proulx [9] and Lord [4] reviewed data on occupant speed, flow, and density. The range of values for occupant speed is shown in Table 1, below. For occupants with mobility impairments, the literature ranges from 0.16 m/s to 0.76 m/s; for occupants with no impairments, 0.49 m/s to 1.3 m/s (not including Fruins crush load value).

3 Current Study

As part of a program to better understand occupant behaviour during building emergencies, the Building and Fire Research 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.

While real emergency data is most desirable and might provide the most realistic predictor of behaviour, it is not as readily available as fire drill data. For practical purposes, fire drill data is often used to study emergency behaviour. A key assumption, consistent with most of the data presented in section 2 of this paper, is that fire drill data can be used to approximate the response of individuals in an actual emergency [9]. 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.

NIST has collected fire drill evacuation data in six high-rise buildings. The data collection has utilized video technology in the stairwells in order to measure individual descent speeds, crowd density, stair entry time (evacuation

Table 1. Occupant Movement Speeds in Stairwells

Year	Movement Speeds (m/s)	Notes	Source
	0.52 ± 0.24^a	18 - 29 year old	Various[b], from Lord et. al. [4]
	0.52 ± 0.23	30 - 50 year old	Various[b], from Lord et. al. [4]
	0.49 ± 0.18	> 50 year old	Various[b], from Lord et. al. [4]
	0.16 - 0.76	Disabled occupant	Various[b], from Lord et. al. [4]
1969	0.58 ± 0.15		Predtechenskii and Milinskii[c] [11]
1972	0.762	Maximum	Fruin [6] from Pauls [8]
1972	0.6096	Moderate	Fruin [6] from Pauls [8]
1972	0.4826	Optimum	Fruin [6] from Pauls [8]
1972	0.2032	Crush	Fruin [6] from Pauls [8]
1988	0.33 ± 0.16	Locomotion disability	Boyce, et. al. [12]
1988	0.7 ± 0.26		Boyce, et. al. [12]
1995	1.1	Relatively fit	Proulx [13]
1995	0.5		Proulx [13]
2001	0.2	9/11 WTC towers	Averill et. al. [14]
2004	0.76 - 1.3	Varied walking angle	Fujiyama [15] adapted by Hostikka[d] [16]
2007	0.57 ± 0.23	Photoluminescent stairwell markings	Proulx [17]
2007	0.64		Hostikka [16]

a - uncertainties are expressed as 1σ.
b - includes data from Fruin [6], Predtechenskii and Milinskii [11], Boyce [12], Proulx [13], Proulx, et. al. [18], Fahy and Proulx [19] and Webber [20].
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.

delay), and stair entry floor (distance evacuated). The primary video analysis identified the following for each occupant to facilitate these measurements:

– time each person exited the stairwell (or entered the stairwell in the case of firefighters ascending the stairwell),
– times that each person passed each camera in the stairwell,
– density or crowdedness of that stair as indicated by the number of other persons nearby each person as they passed by each camera in the stairwell, and
– floor of entry for each person.

This paper focuses on the first three of these evacuations. The three buildings included in this paper ranged from six to 18 stories in height and were typical office occupancies. Typically 100 to 300 people used a stairway for evacuation. The stairs in these three buildings varied in width from 0.91 m to 2.24 m wide. A brief description of the three buildings is shown in Table 2.

Table 2. Buildings Included in Current Study

	Building 1	Building 2	Building 3
Occupancy	Office	Office / Educational	Office
Floors	6	11	18
Stair Width[a] (m)	1.44 / 1.54[b]	1.22 / 1.22	0.91 / 0.91
Stair Riser (mm)	302	186	191
Stair Tread (mm)	283	238	254
Exit Width (m)	1.83 / 1.73	2.01 / 2.39	0.91 / 0.91
Evacuees	127 / 150	119 / 15	286 / 197
Evacuation Time (s)	411	442	1031

a - Full stair width including handrails.
b - Stairwell A widened to 1.68 m at the third floor. Stairwell B widened to 2.24 m at the third floor.

Six-story Building - The large office building had with seven wings adjoining and parallel to each other. During the drill, evacuation from two of 14 stairwells was observed. The stairwells (Stairwell A, 1.44 m wide and Stairwell B, 1.54 m wide) were in separate, neighbouring 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 accessible from all rooms and floors and led occupants into a lobby through double doors. After travelling through the lobby, occupants travelled down a small set of steps to a vestibule. The vestibule then led to the exterior of the building. A total of 277 occupants were observed in the quasi-unannounced drill[1] (127 in Stairwell A and 150 in Stairwell B). In Stairwell B, two groups of three firefighters each travelled up the stairwell at 40 s and 80 s after activation of the building fire alarm to study the impact of firefighter counterflow on the descending occupants. Total evacuation time for this fire drill was 411 s.

Eleven-story Building - The building was an office occupancy for an educational institution housing faculty offices and research laboratories. Typical of many office buildings, there were two stairwells, both 1.22 m wide, located at opposite corners and accessible from all floors of the building. Both stairwells widened at the lower floors. One of the stairwells was directly adjacent to the building elevators. The stairwells opened directly to the exterior of the

[1] Occupants were told that a fire drill would take place in the near future, but were not told when the evacuation would take place. Normal alarm procedures were followed for the drill without further notification of the nature of the event.

building. 134 occupants took part in the quasi-unannounced drill, with more than 89 % using the stairwell adjacent to the elevators. Total evacuation time was 442 s.

Eighteen-story Building - The building housed a business occupancy in three wings adjoining a fourth corridor at one end of the wings. Of the twelve 0.91 m stairwells available for egress, visual observations were made in five. Two of these, located in separate wings, were used for this paper. Several of the stairwells exited to the lobby area on the fifth floor through single 0.91 m wide doorways; others continued to the ground floor and exited directly out of the building. The lobby area exited directly to the exterior of the building. 727 occupants participated in the quasi-unannounced fire drill (286 in Stairwell 1 and 197 in Stairwell 12). In Stairwell 12, a total of 17 firefighters travelled up the stairwell in two groups following activation of the building fire alarm. Total evacuation time was 1031 s.

A summary of the pre-evacuation delay times and average stairwell descent speeds is shown in Table 3. Figure 1 shows the range of individual movement speeds for the three fire drills. For each camera location, the mean speed is shown for occupants who were first observed evacuating at that camera location (With cameras typically located at every other floor landing, this means entering either at the floor where the camera is located or at one floor above the camera location). With the possible exception of the first three floors of the 6-story building, the data generally fall within experimental uncertainty of each other for all floors in the three buildings.

Table 3. Occupant Movement Speeds (with Standard Deviation) in Stairwells

Building	Pre-evacuation Delay Time (s)	Speed (m/s)
6-Story, No FF	144 ± 68	0.83 ± 0.18
6-Story, FF	140 ± 53	0.73 ± 0.26
11-Story	89 ± 54	0.62 ± 0.10
18-story, No FF	220 ± 144	0.40 ± 0.09
18-Story, FF	188 ± 93	0.54 ± 0.18

The distribution of stairwell movement speeds in the three buildings shown in Figure 2a and the cumulative distribution functions shown in Figure 2b provide additional details of the range of speeds in the evacuations. Overall, 19 % of the occupants move slower than 0.4 m/s (and these are nearly all in the 18 story building; less than 1 % of the occupants in the 6- and 11-story buildings moved slower than 0.4 m/s) and 6 % move faster than 1 m/s. Profiles for stairwells with fire fighter counterflow show a broader variation in movement speeds than those without in both the 6- and 18- story buildings. In the six story building, occupants moved slower in the stairwell with firefighters compared to the stairwell without firefighters while they moved

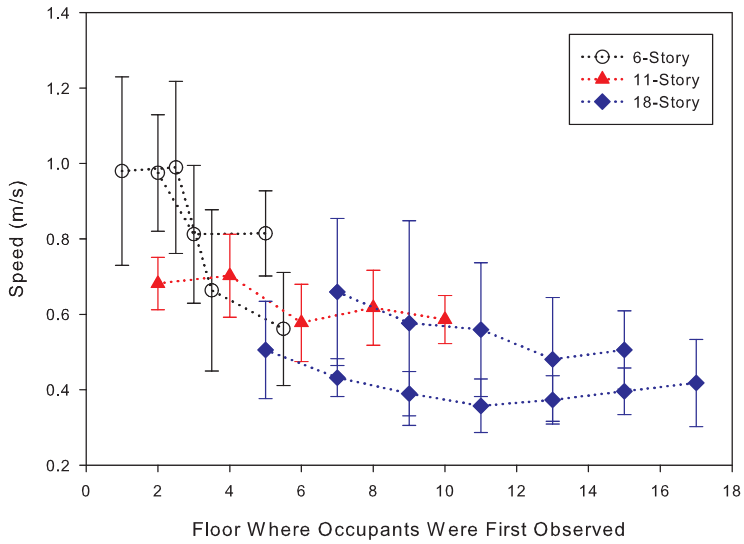
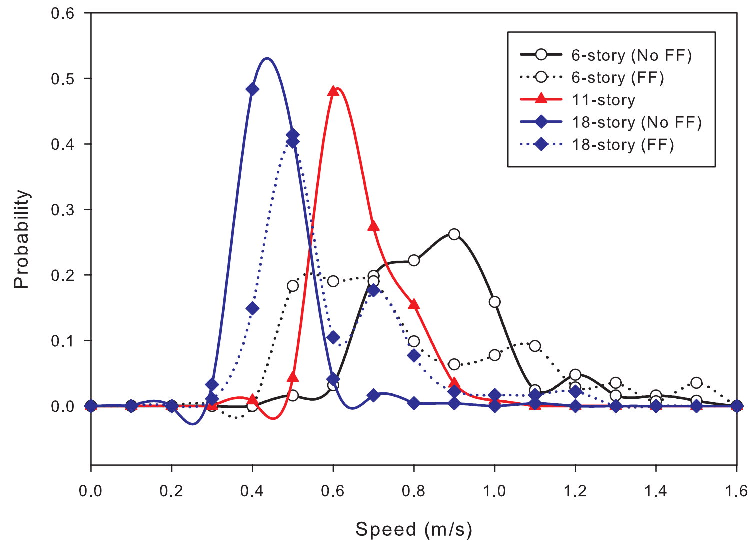


Fig. 1. Occupant movement speeds (with standard deviation) down stairwells in three fire drill evacuations.

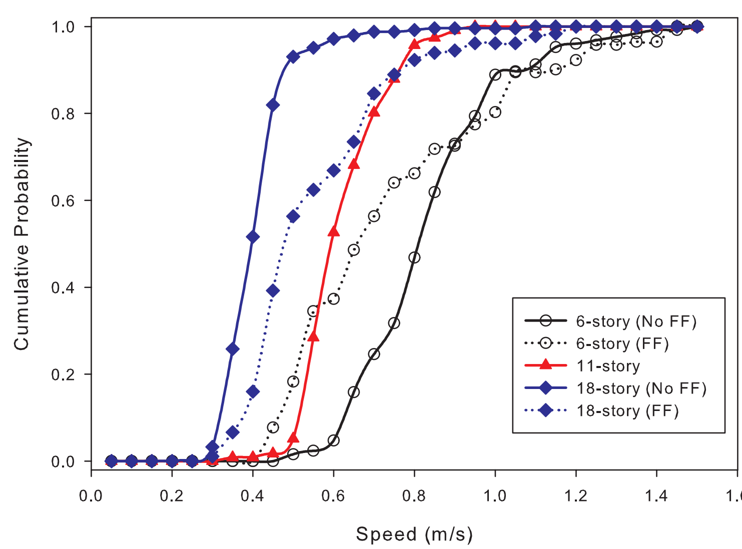
faster in the 18-story building. This is likely due to congestion in the 18-story building stairwell from the much higher occupant load in the stairwell without firefighters. Additional data are needed to understand and verify the observed differences.

Comparing the recent evacuations to historical data (Figure 3) shows these data are typically within the range of data in the literature and quite similar to the "optimum" or moderate movement speed of Fruin [6]. Values for very dense evacuations (Fruin's crush load [6], the 9/11 World Trade Center evacuation [14] 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, particularly to understand the impact of emergency conditions compared to fire drill evacuations.

To investigate the underlying causes for differences in movement speeds, a causal model was constructed to explore the components affecting occupant descent speeds in the stairwells. These included the typical engineering parameters that can be directly measured during the evacuation as follows:



a - Probability Distribution



b - Cumulative Probability Distribution

Fig. 2. Cumulative distribution function of movement speeds down stairwells in three fire drill evacuations.

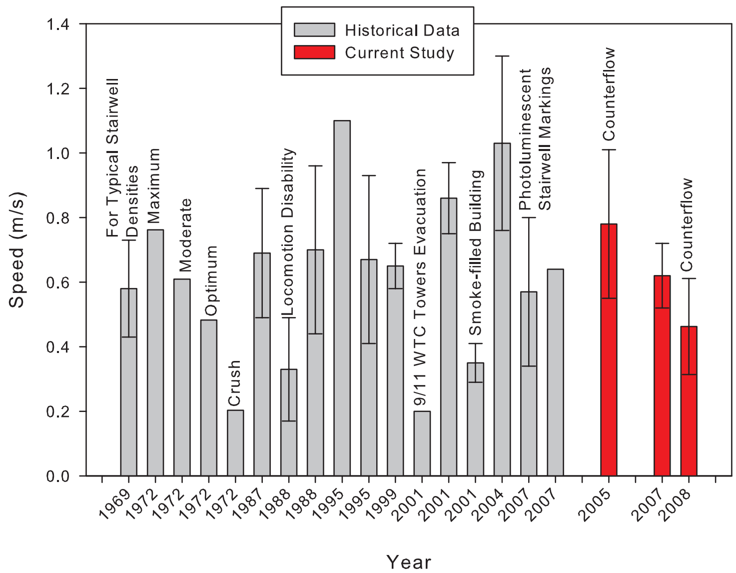


Fig. 3. Comparison of current study stairwell descent speeds with literature values. Where available, data points include standard deviation of average movement speeds.

1. Delay in evacuation initiation. Delay evacuation may cause occupants to encounter more or fewer people in the stairwell which may impact their speed (For evacuation initiation delay, only data from the 6- and 11-story buildings were available. Data from the 18-story building is forthcoming).
2. Distance travelled during evacuation. Evacuation from higher floors may lead occupants to encounter more congestion in the stairwells or allow occupants to tire more than those evacuating from lower floors leading to lower movement speeds.
3. Presence or absence of firefighters travelling in flow counter to the descending occupants. Firefighters moving up the stairwell may impede those descending the stairs or may encourage the occupants to move more quickly.
4. Stairwell width. Wider stairwells may allow occupants to descend side by side or allow faster evacuees to pass slower ones. Narrow stairs may lead to congestion.
5. Density of people encountered during the evacuation. The presence additional persons in the stairwells nearby each evacuating occupant that may impede the evacuation of a given building occupant by limiting the maximum attainable speed of the occupant (For occupant density, only

data from the 6- and 11-story buildings were available. Data from the 18-story building is forthcoming).

Using multivariate linear regression, we can relate these factors to movements speed in a simple regression equation

$$\hat{Y} = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + e_{et} \ , \qquad (1)$$

where the β-coefficients, β_1, β_2, ... , β_5 are coefficients of the regression, X_1, X_2, ... , X_5 are the vectors of the measured engineering parameters above, $\hat{Y}$ is the vector of measured occupant stairwell descent speed, and e_{et} is an added error term that includes all causes not specifically included in the model. The magnitude and sign of the β-coefficients show the relative strength of the relationship between each variable the measured movement speed. That is, how important is the variation in variable X in predicting the variation in speed relative to other variables included in the model? For this simple model, only direct effects of each parameter on movement speed are considered.

Figure 4 shows the results of the causal analysis. Numbers on the connector arrows in Figure 4 are the β-coefficients of the regression for each variable. Firefighter counterflow, delay, distance travelled, and stair width each had statistically significant impact on occupant movement speed during the evacuation. For example, occupant evacuation speed was inversely related to the distance travelled by the occupant; the higher the starting floor, the slower the overall movement speed. Distance is seen as twice as important as firefighter counterflow or stair width and three times as important as pre-evacuation delay in predicting speed. Stairwell density did not vary sufficiently in the two evacuations included to see a significant impact on evacuation speed.

However, the most notable result of the regression is that all of these easily measurable engineering variables together accounted for only 13 % of the variance in occupant speed. Thus, the vast majority of the variance in occupant evacuation speed is not explained by these typical engineering parameters used to describe stairwell flow. Physiological and behavioural factors may be more important in determining occupant speed. While occupant demographics were not available for the current study, NIST [14] has estimated that 6 % of the occupants who evacuated the World Trade Center towers on September 11, 2001 reported having a mobility impairment that hindered their evacuation. Kuligowski and Gwynne [21] discuss the need to account for human behaviour and note that inaccurate results from simplifications about behaviour can lead to unsafe building designs and procedures. Clearly there is a need to better understand all the factors that impact the ability of building occupants to take appropriate protective action in the event of a building emergency.

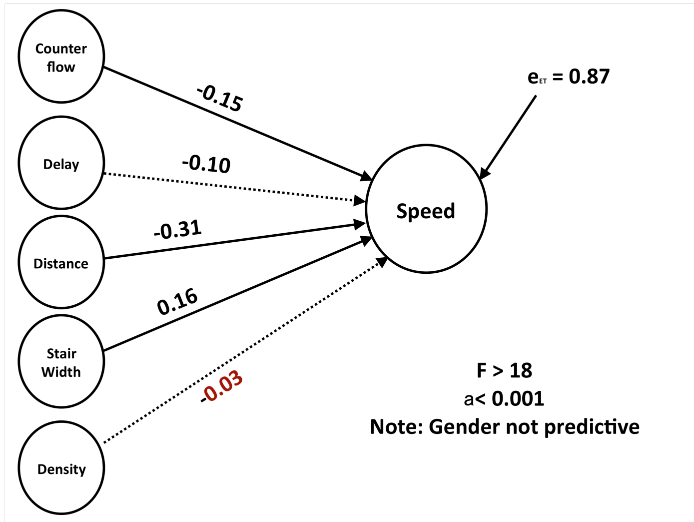


Fig. 4. Model of occupant stairwell descent speed.

4 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 three new fire drill evacuations. The following conclusions are evident from the study:

- An "engineering approach" is insufficient to understand variance in occupant stairwell descent speeds. Better understanding of behavioural and physiological factors may improve explained variance across evacuations.
- Firefighter counterflow is a small but significant impact on stairwell movement speeds (in a six story building). The effect in taller buildings is yet to be studied.
- Understanding the context of observed evacuation drills is critically important. For the observed densities in the current study, stairwell width is a minor parameter. At higher occupant densities, literature suggest that stairwell width should be important [7].
- Early evidence does not support the hypothesis that people are moving more slowly, but additional research is needed to understanding movement speeds for a range of buildings and environmental conditions.

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