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 measureable 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 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. To date, NIST has collected fire drill evacuation data in eight office building occupancies ranging from six 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.

Introduction

Timing of 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, 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 [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. 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 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.

As part of a program to better understand occupant movement and behavior 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 codes and standards requirements. To date, NIST has collected fire drill evacuation data in eight office building occupancies ranging from six to 62 stories in height that have included a range of stairwell widths and occupant densities.

This paper builds on a paper from the previous conference [5] to examine evacuee movement in four additional buildings, local movement speeds in addition to overall movement speeds, and an initial examination of underlying factors that may influence occupant evacuation.

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 [6]. 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.

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. Additional information included gender, body size, location on the stairs, handrail usage, and whether anything was being carried by each occupant.

All of the buildings were typical office occupancies with up to 500 evacuees in a stairwell. These data are available on the NIST website at http://fire.nist.gov/egress/. A summary of the four buildings included in the current study is shown in Table 1, with additional details on each of the buildings available on the website.

Table 1. Stairwell geometry and evacuation details for buildings included in the 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	436 / 368	255 / 292 / 340 / 197	249 / 356	704 / 538
Evacuation time (s)	1022	1192	1090	1002

[a] Full stair width including handrails

Overall Movement Speed

A summary of pre-evacuation times and average stairwell descent speeds is shown in Table 2. The average evacuee speeds in all stairwells of the buildings are within experimental variability (as expressed by one standard deviation). Figure 1 shows average local movement speeds for the four fire drills, including data from the drills included in an earlier paper [5].

Table 2. Pre-evacuation time and stairwell movement speeds in three fire drill evacuations

Building	Pre-evacuation delay time (s)	Average speed (m/s)
10-Story	171 ± 124	0.44 ± 0.19
18-Story	224 ± 146	0.44 ± 0.15
24-Story	137 ± 86	0.56 ± 0.12
31-Story	149 ± 88	0.52 ± 0.10

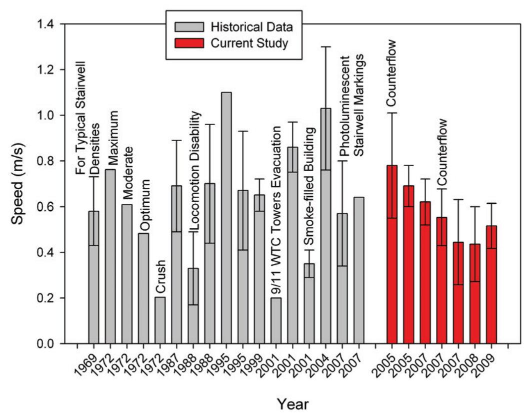
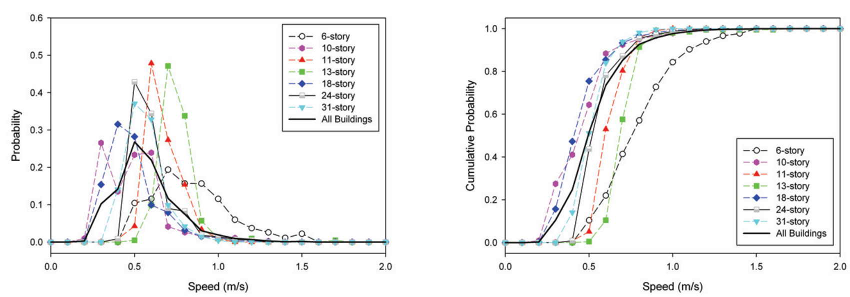


Fig. 1. Comparison of current study average stairwell descent speeds with literature values. Where available, data points include standard deviation of average movement speeds.

Figure 1 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 [7].

Values for very dense evacuations (Fruin's crush load [7] and the 9/11 World Trade Center evacuation [8,9]) 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.



(a) Probability Distribution

(b) Cumulative Probability Distribution

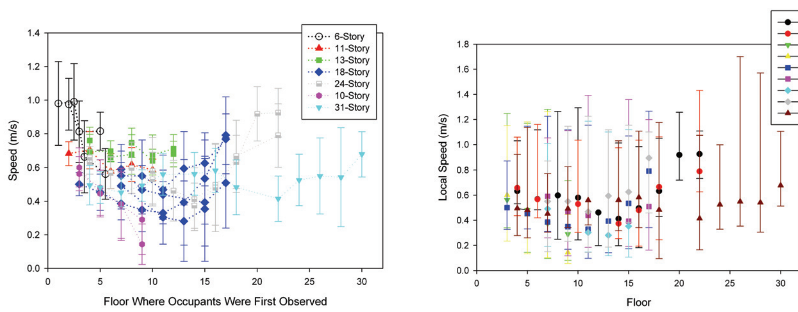
Fig. 2. Distribution of movement speeds down stairwells in several fire drill evacuations

The distribution of stairwell movement speeds in the 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 (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 [5]), 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. However, with the overlapping standard deviations between the 6-story building and the other buildings, the difference is not likely to be significantly different.

Local Movement Speeds

Overall movement speed, arguably the most commonly reported value for evacuee movement in stairwell evacuation, 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.

Figure 3a 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 Figure 3b. 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.



(a) Average with standard deviation (b) Range of local speeds

Fig. 3. Local occupant movement speed down stairwells in several fire drill evacuations.

Some of the variation in local speed is attributable to changing evacuee density in the stairwell as the evacuation proceeds. As each evacuee entered a camera view travelling down a stairwell, the local density is calculated from the number of other evacuees ahead in the path of evacuation and the total area of stairs and landing surfaces in the same camera view.

Figure 4 shows individual local speed as a function of density for all evacuees in the 24-, 10-, 18-, and 31-story buildings. Also shown in the figure is the correlation for evacuation speed as a function of density from the SFPE Handbook of Fire Protection Engineering [6] based on the data of Fruin [7], Pauls [10], and Predtechenskii and Milinskii [11]. 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. A better understanding of the underlying theory and of evacuee behavior would be required to justify any particular correlation to the data.

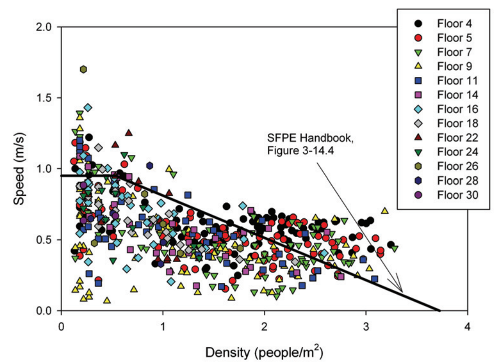


Fig. 4. Local speed as a function of local density for evacuees in all stairwells of 10-, 18-, 24-, and 31-story buildings during fire drill evacuations.

Regression Modeling

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. The dependent variable, local movement speed, was calculated based on the time difference between when the occupant was seen on adjacent cameras (typically 2 floors apart in a stairwell) and the known distance between the cameras. Eight independent variables, stairwell, gender, carrying objects, exit lane, handrail use, pre-evacuation time, density, and travel distance, were included in the model.. The first five variables were categorical variables and the final three variables were continuous variables.

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 3). The correlation was significant at the less than 0.001 level. For the categorical variables, reference values were chosen simply to allow comparison (male, not carrying anything, middle exit lane, not using the handrail, and the 31-story

[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.

building stairwell being defined as 0). 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.

Table 3. Main effects regression model for local movement speed

	Unstandardized Coefficients		Standardized Coefficients	
Model	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-Evacuation 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

The data was examined to ensure that the assumptions of regression modeling were met. Zero-order correlation matrices were examined and no multicollinearity was detected. Heteroscedasticity was tested by graphing the residuals versus the independent variables. Two of the variables, density and pre-evacuation time, failed the test. While the coefficients are still accurate, the standard deviations might not be. The coefficient for pre-evacuation 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 [7]. 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 carrying anything were slower than those who were not while using the handrail did not cause a significant change. Evacuees travelling near the edges of the stairwells travelled slower than those in the middle. Men travelled 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-evacuation 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. Two general trends in the interactions were noted. The first set involved interactions with density and 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 uniform. In the main effects model, this difference will cause several of the terms to appear less significant than they are in reality. 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. Individual characteristics 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-evacuation 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. 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 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.

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.

References

1 Kuligowski, E.D., R. D. Peacock: Review of building evacuation models. Technical Note 1471, National Institute of Standards and Technology, Gaithersburg, MD, 2005.
2 Gwynne, S., E. R. Galea, M. Owen, P. J. Lawrence: Further Validation of the buildingEXODUS Evacuation Model Using the Tsukuba Dataset. Rep. No. 98/IM/31, University of Greenwich, London, 1998.
3 Gwynne, S., E. R. Galea, M. Owen, P. J. Lawrence: Validation of the buildingEXODUS Evacuation Model. Rep. No. 98/IM/29, University of Greenwich, London, 1998.
4 Lord, J., B. Meacham, B. Moore, R. Fahy, G. Proulx: Guide for evaluating the predictive capabilities of computer egress models. GCR 06-886, National Institute of Standards and Technology, Gaithersburg, MD, 2005.
5 Peacock, R.D., J. D. Averill, E. D. Kuligowski,: Stairwell evacuation from buildings: What we know we don't know. In *Pedestrian and Evacuation Dynamics 2008*, ed. W. W. F. Klingsch, C. Rogsch, A. Schadschneider, and M. Schreckenberg. NewYork: Springer, 2010.
6 G. Proulx. Movement of People: The Evacuation Timing, chapter 3-13, pages 3-341 – 3-366. In *The SFPE Handbook of Fire Protection Engineering*. Society of Fire Protection Engineers, Bethesda, MD, third edition, 2002.
7 Fruin, J.J. Pedestrian Planning and Design, Revised Edition). ElevatorWorld, Inc., Mobile, AL, 1987.
8 Averill, J. D., D. S. Mileti, R. D. Peacock, E. D. Kuligowski, N. Groner, G. Proulx, P. A. Reneke, and H. E. Nelson. Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Occupant Behavior, Egress, and Emergency Communication. NIST NCSTAR 1-7. National Institute of Standards and Technology. Gaithersburg, MD, 2005.
9 Galea, E. D., L. Hylse, R. Day, A. Siddiqui, G. Sharp, K. Boyce, L. Summerfield, D. Canter, M. Marselle, and P. V. Greeall, "The UK WTC 9/11 Evacuation Study: An Overview of the Methodologies Employed and Some Preliminary Analysis." In *Pedestrian and Evacuation Dynamics 2008*, ed. W. W. F. Klingsch, C. Rogsch, A. Schadschneider, and M. Schreckenberg. NewYork: Springer, 2010.
10 Pauls, J. L., Effective-Width Model for Evacuation Flow in Buildings. In *Proceedings, Engineering Applications Workshop,* Society of Fire Protection Engineers, Boston, 1980.
11 Predtechenskii, V.M. and Milinskii, A.I., *Planning for Foot Traffic Flow in Buildings,* Amerind Publishing Company, Inc., New Delhi, 1978.