NISTIR 7425

Accounting for Emergency Response in Building Evacuation: Modeling Differential Egress Capacity Solutions

Jason D. Averill
Weiguo Song

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NISTIR 7425

Accounting for Emergency Response in Building Evacuation: Modeling Differential Egress Capacity Solutions

Jason D. Averill
Building and Fire Research Laboratory

Weiguo Song, Ph.D.
Guest Researcher
Building and Fire Research Laboratory
and
State Key Laboratory of Fire Science, USTC, China

April 2007

U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

Technology Administration
Robert Cresanti, Under Secretary of Commerce for Technology

National Institute of Standards and Technology

**Accounting for Emergency Response in Building Evacuation:
Modeling Differential Egress Capacity Solutions**

Abstract: The impact of firefighter response on the progress of the building evacuation is not typically considered. Responders use of the stairs while occupants are evacuating can significantly increase total building evacuation time. To account for emergency response, this analysis considered whether adding capacity through extra stairwell width was equivalent to providing the same total egress capacity through an additional stairwell. An egress simulation with a counterflow submodel was calibrated against recent fire-drill experimental results to demonstrate the capability of the model to produce meaningful evacuation results. The model was then applied to a hypothetical 50 story office building with 350 occupants per floor. When comparing equivalent total width, additional stairwells outperform wider stairwells from the perspective of evacuation performance, as well as firefighter ascent times. A third stairwell can completely mitigate the effect of firefighter response or even improve the building evacuation time compared to two stairwells with no firefighter response.

Background: The ICC Terrorism Resistant Buildings (TRB) Committee has proposed a change to Section 403 of the International Building Code (IBC), which would require one additional stairwell (one greater than otherwise required) for all high-rise buildings (other than R-2) taller than 420 ft (128 m). The proposal would provide greater egress capacity than currently required, recognizing that one stairwell may become unusable during evacuation due to the introduction of smoke and heat and blockage by fire hoses once suppression operations begin.

Objective: Perform computer egress modeling to provide quantitative comparisons of different stairwell configurations with and without emergency response interaction.

Model Description

The computer model is a modified form of a biased random walk model without back step.[1] The model is defined in a two-dimensional grid, of which each site can be occupied by a pedestrian or be empty. Each pedestrian can move to a neighboring site with certain probabilities. Usually, every pedestrian has a drift to move to the preferential site. All the possible configurations of downward walkers are demonstrated in Figure 1. The movement probabilities can be calculated with Equation 1.

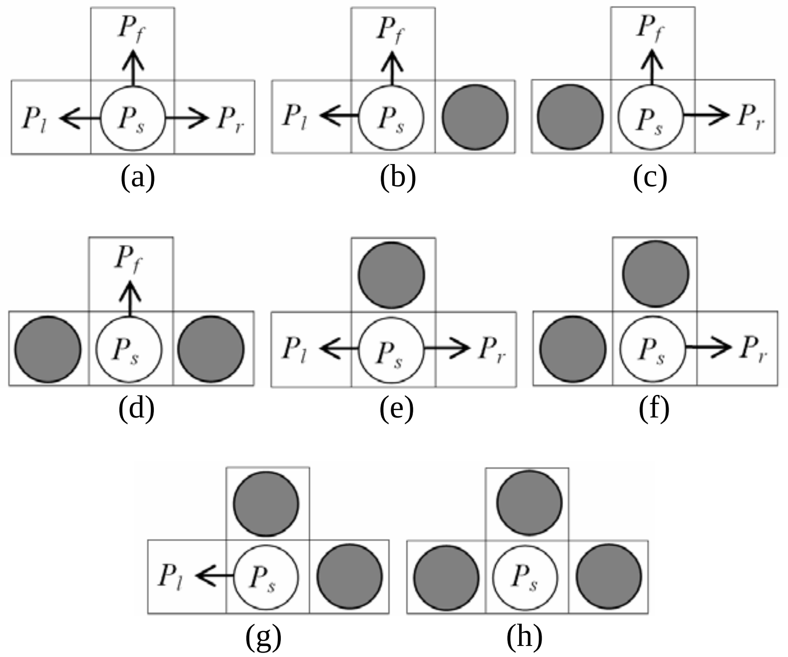


Figure 1: Basic Movement Rules

P_f is the probability of moving forward; P_l is the probability moving leftward; P_r is the probability of moving rightward; and P_s is the probability of stopping. The values of probabilities corresponding to Figure 1 are as follows:

(a)	P_f=0.8	P_l=0.05	P_r=0.15	P_s=0.0
(b)	P_f=0.8	P_l=0.05	P_r=0.0	P_s=0.1
(c)	P_f=0.8	P_l=0.0	P_r=0.15	P_s=0.05
(d)	P_f=0.8	P_l=0.0	P_r=0.0	P_s=0.2
(e)	P_f=0.0	P_l=0.05	P_r=0.15	P_s=0.8
(f)	P_f=0.0	P_l=0.0	P_r=0.15	P_s=0.85
(g)	P_f=0.0	P_l=0.05	P_r=0.0	P_s=0.95
(h)	P_f=0.0	P_l=0.0	P_r=0.0	Py=1.0

Note that all of the probabilities sum to 1.0, as shown in
(Eq. **1**.)

$$\mathbf{P_f + P_l + P_r + P_s = 1.0} \qquad \textbf{(Eq. 1)}$$

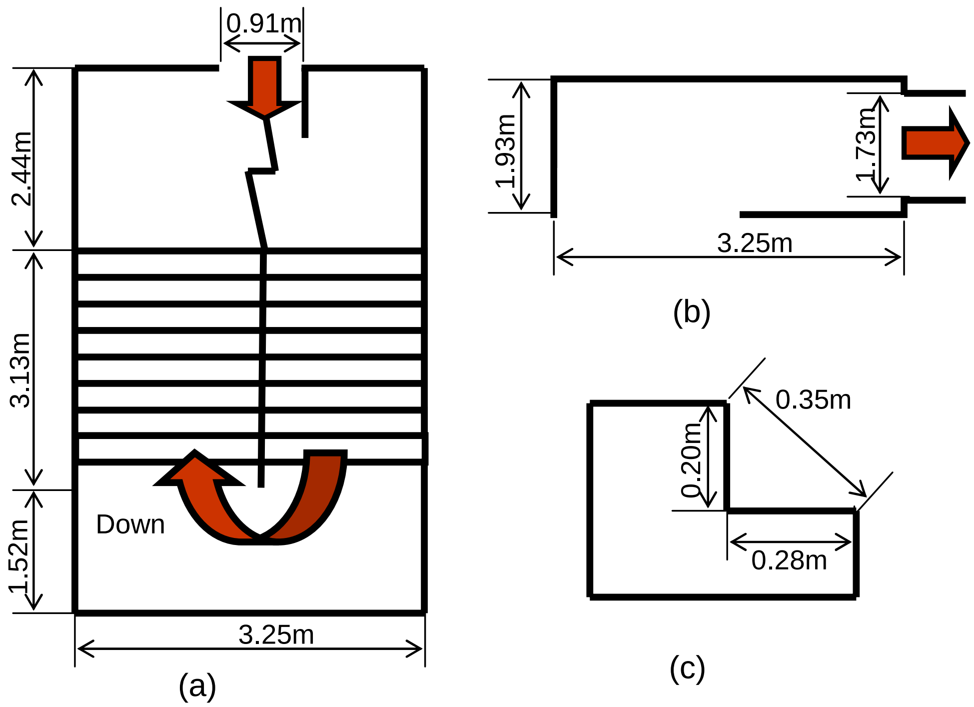
Stairwell evacuation also has its own characteristics, including right-side walking tendency and firefighter avoidance. People in a stairwell have a right-side walking tendency. There are three reasons for a right-side walking requirement in the model. First, right-side walking is consistent with the traffic rules in the U.S. with which people are familiar. Second, the staircase descends and rotates in clockwise direction, so right-side walking is inner-side walking, which results in shorter walking distance relative to left-side walking. Third, for firefighters, adopting a right-side walking strategy will avoid collisions with occupants. So both pedestrians and fire fighters walk with a right-side tendency. Fire fighters walk on the left side or middle only if the right side of the stair is blocked by occupants. Firefighter avoidance means occupants make room for firefighters when they encounter each other. That is a significant difference from the traditional definition of counterflow where pedestrians with opposite walking direction compete with each other for the walking opportunities.

Model Validation

The model was calibrated against data collected from an unannounced evacuation drill observed in a six-story office building.[2] During the evacuation, two stairwells (designated "Stairwell A" and "Stairwell B") were observed. The stairwells were in separate, neighboring wings. The floor areas serving the stairs were nominally identical, with the same number of elevators, stairwells, and exterior exit doors. The stairwells in each wing were equally accessible from all rooms and floors. Both stairwells deposited occupants into a lobby through a set of double doors, where they subsequently made their way outside.

Figure 2 shows the geometry of the stairwell and tread. The stairwell had a width of 3.25 m and a length of 7.09 m. Occupants exited the stairwell through a 1.73 m wide double exit door. In other floors, occupants entered the stairwell through a 0.91 m wide exit door and merge with those from upper floors. In both Stairwells there were eight steps per flight. The only exception was in Stairwell B between floor 2 and floor 1. From floor 2 to floor 1.5 there were six steps, and from floor 1.5 and floor 1 there were 10 steps; this averaged out to eight steps for each flight. The steps in both stairwells had the same tread and depth dimensions. The rise of each stair was 0.2 m (8 in), and the tread was 0.28 m (11.1 in). The diagonal distance of each stair was 0.35 m (13.7 in).

There was no firefighter counterflow in Stairwell A. The walking speed of occupants was determined by Figure 4, where the average speed is plotted against different occupant density. The free walking speed, or maximum walking speed, is the speed of an occupant when there is no obstacle nor occupants surrounding him. In fact, it is the speed when occupant density is close to 0. In both Stairwell A and Stairwell B, the average walking speed shows an approximately monotonic decrease with the increase of occupant density. It is possible to obtain the free walking speed with the measured relation between walking speed and occupant density.



(a) stairwell over second floor (b) first floor (c)tread geometry

Figure 2: Floor and Tread Geometry

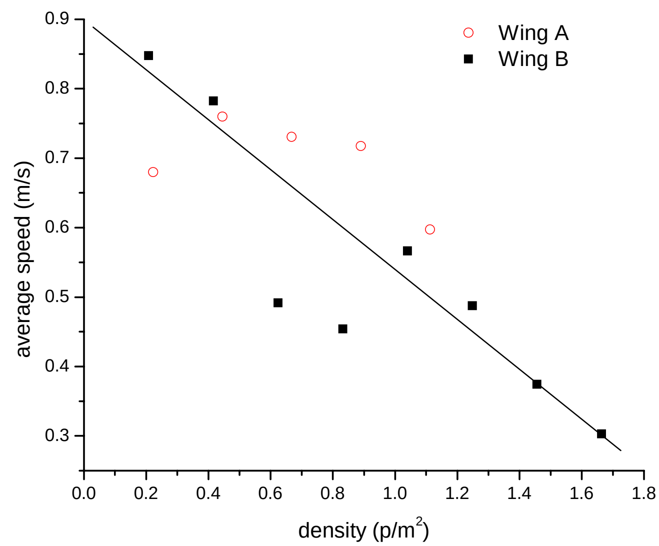
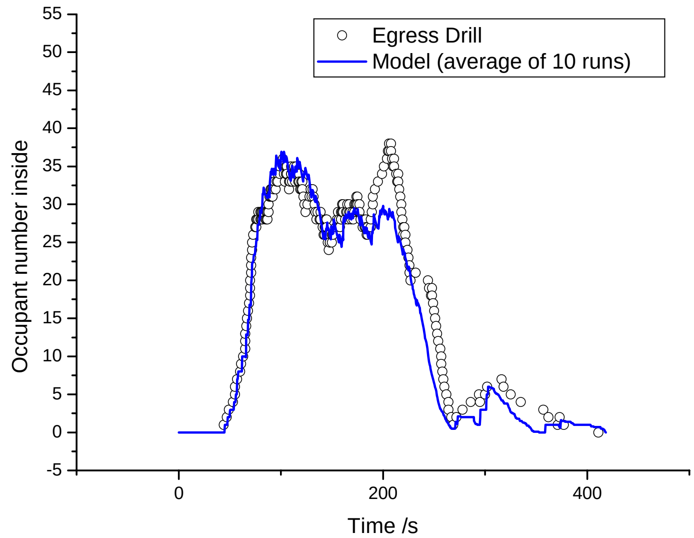


Figure 3: Occupant Speed Versus Density

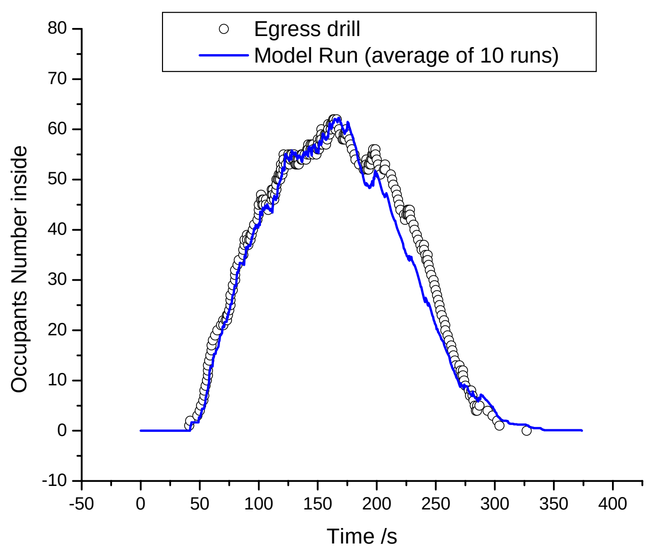
The drill was conducted in 2005 on a sunny, warm, and clear day. DV-cameras were used to record the egress process. The timeline of the egress drill was as follows.

- At t = 0 s, the fire alarm was activated.
- At t = 80 s, the first group of firefighters was sent into Stairwell B.

- At t = 149 s, the second group of firefighters was sent into Stairwell B.
- The egress drill was completed after all people went out.



(a) Stairwell A (no counterflow)



(b) Stairwell B (with counterflow)
Figure 4: Change of occupant number inside stairwell with time

Figure 4 shows the change in the number of occupants inside the stairwell as a function of time for both stairwells. The entrance time for an individual occupant to the stairwell was an input condition to the model. The occupant movement speeds, interactions with other occupants and responders (if any) were calculated using the model. The differences in occupant density between Stairwells A and B due to the firefighter counterflow were well captured by the model.

Modeling Scenario: The objective of this study was to understand the differences, if any, between two commonly discussed strategies for increasing egress capacity: adding additional width to existing stairs, or adding an additional stair. Therefore, a challenging evacuation scenario was developed in order to clearly demonstrate any differences in evacuation times. The modeling scenario selected was a high-rise office building with a relatively high occupant load per floor. The model building was a 50 story high-rise office building with 350 persons per floor. The evacuation mode was full-building evacuation and input parameters were chosen to emphasize the effect of the primary variable (stair width) on evacuation time. It was assumed that: (a) there were no occupant evacuation initiation delays, (b) there were no mobility impaired occupants, and (c) that occupants left by the nearest available exit.

A baseline scenario, where firefighters do not use the stairwells until the building is evacuated, was calculated to quantify the impact of the emergency response on the evacuation time. Subsequently, evacuation times were calculated varying three basic parameters: stair width, response scenario, and location of the fire in the building. Additionally, the ascent time for the firefighters is calculated. Note that ascent time does not include the time that it would take to stage and mount an attack on the fire floor, nor the physical impact that the ascent has on the overall ability of the firefighter to subsequently fight the fire.

Evacuation times were calculated for two stair width configurations: (a) a two person wide stair (roughly 1100 mm (44 in) clear width); and (b) a three person wide stair (roughly 1700 mm (66 in) clear width). The results were also calculated for two fire department response conditions. In the first scenario, referred to as the 'counterflow' scenario, firefighters ascend the stairs against the flow of the descending occupants until they reach the fire floor, when the stairwell is taken out of service for use by occupants above the fire floor. Occupants above the fire floor in the counterflow stairwell are assumed to immediately exit the stairwell and transfer to the nearest available stairwell. The counterflow scenario assumes that a new group of four firefighters enters the stairwell every 5 min and begins to climb the stairs. Every 20 floors, the firefighters stop and rest for 5 min (not in the stairwell) before resuming their climb to the fire floor.[†] In the second scenario, referred to as the "closed stairwell' scenario, firefighters close one stairwell to occupant use after 10 min in order to maintain a dedicated attack stairwell. Again, occupants are assumed to immediately exit the attack stairwell and enter the nearest available stairwell. The firefighter ascent times are determined by the time when the first firefighter reaches the fire floor. Finally, three different fire locations were selected within the building. The fire high in the building was located on floor 50. The fire in the middle of the building was located on floor 25. The fire low in the building was located on floor 5.

[†] This estimate was based on reports from the NIST WTC Investigation. See NCSTAR 1-8 "The Emergency Response Operations" pp. 89 – 91, available at http://wtc.nist.gov. Individual firefighter climb rates may vary and resting may or may not be necessary.

Results:
Table 1 shows the results of the baseline evacuation modeling scenarios. National model codes would currently require two 1100 mm (44 in) stairwells in a 50 story office building with an occupant load of 350 persons per floor (unless travel distance requirements required an additional stair). Under ideal evacuation circumstances (described above) and assuming that the fire service did not utilize the stairways during the occupant evacuation time period, the building would evacuate in approximately 179 min (three hours). In the event that one of the two stairwells was out of service, the evacuation time would approximately double (although this scenario was not modeled). Next, the benefits of requiring additional egress capacity were evaluated. Two stairs providing three flow lanes each (approximately 1700 mm (66 in) clear width) would decrease the building evacuation time by approximately 40 min, or 22 %, compared to two stairs each providing two flow lanes. Alternatively, three stairs, each providing two lanes of flow (approximately 1100 mm (44 in) clear width), would decrease the building evacuation time by 61 min, or 34 %.

Table 1: No fire in the building, full building evacuation (baseline)

Scenario	Occupant Evacuation Time (min)
Two 44 in stairs	179
Two 66 in stairs	141
Three 44 in stairs	119

The results in Table 1 do not account for the impact of the emergency response on the building evacuation time. Assuming that the firefighters do not use the elevators, they are likely to employ one of two strategies in order to initiate suppression activities: walking up the stairs against the flow of descending occupants (counterflow) and closing the attack stair when reaching the fire floor; alternatively, the fire service may close one of the stairwells to occupant use upon arrival (assumed to be 10 min). The impact of the two fire service strategies, along with the fire location (high, medium, and low in the building) and the two stairway configurations, on the overall evacuation time is summarized in Table 2. Figure 5Figure 7 show the same information graphically.

Table 2: Summary of Modeled Evacuation and Ascent Times

Scenario		Firefighter Ascent Time (min)		Occupant Descent Time (min)	
		Counterflow	Closed Stairwell	Counterflow	Closed Stairwell
Fire on Floor 50	Two 66 in stairs	129	41	161	274
	Three 44 in stairs	108	41	136	174
Fire on Floor 25	Two 66 in stairs	67	25	221	274
	Three 44 in stairs	61	25	156	174
Fire on Floor 5	Two 66 in stairs	12	11	N/A	274
	Three 44 in stairs	12	11	N/A	174

Figure 5: Evacuation and Response Times for Fire at Floor 50

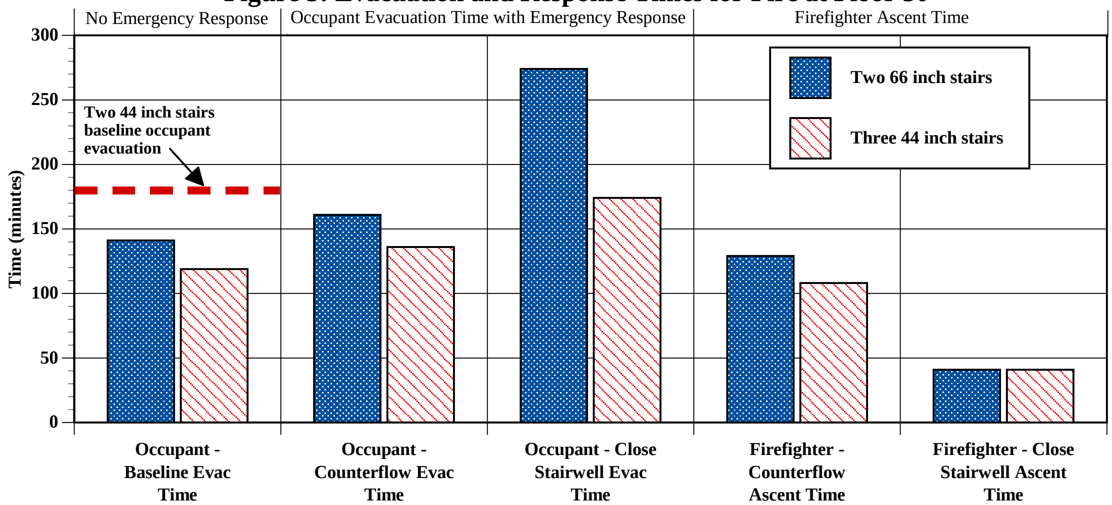


Figure 6: Evacuation and Response Times for Fire at Floor 25

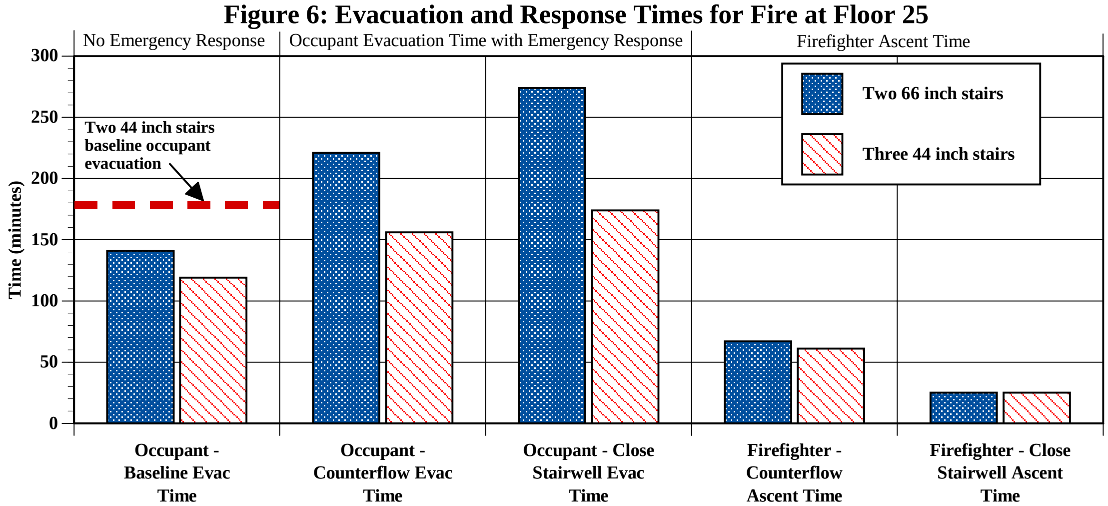
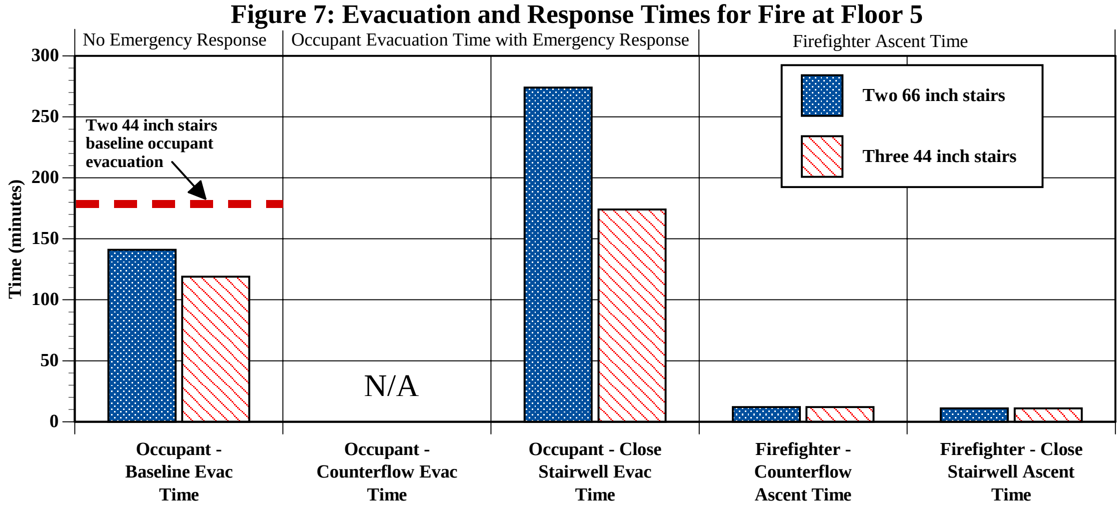


Figure 7: Evacuation and Response Times for Fire at Floor 5



The impact of counterflow on total evacuation time is dependent upon the location of the fire and the configuration of the stairwell. The reason that the fire low in the building has a more significant impact on the building evacuation time than a fire higher in the building is due to the fact that the firefighters close the stairwell for use above the fire floor once they arrive at the fire floor.

Table 3: Impact of Emergency Response on Evacuation Time*

Scenario		Difference in Evacuation Time Comparing Same Stair Configuration With and Without Emergency Response		Difference in Evacuation Time Comparing Alternative Stair Configuration With Emergency Response to Two 44 in Stairs Without Emergency Response	
		Counterflow	Closed Stairwell	Counterflow	Closed Stairwell
Fire on Floor 50	Two 66 in stairs	14 %	94 %	-11 %	52%
	Three 44 in stairs	14 %	46 %	-24 %	-3 %
Fire on Floor 25	Two 66 in stairs	57 %	94 %	23%	52 %
	Three 44 in stairs	31 %	46 %	-13%	-3 %
Fire on Floor 5	Two 66 in stairs	N/A	94 %	N/A	52 %
	Three 44 in stairs	N/A	46 %	N/A	-3 %

*** Positive indicates longer evacuation times and negative indicates shorter evacuation times.**

Accounting for emergency response in high-rise buildings may significantly increase the expected building evacuation time. Table 3 shows percent increase in total building evacuation time when the impact of emergency response is calculated compared to building evacuation time when the emergency response is neglected. Closing a stairwell after 10 min has the effect of proportionally increasing the evacuation time: removing one of the two stairwells nearly doubles the evacuation time (94% increase). For a building with three stairwells, removing one-third of the stairwells increases the evacuation time by 46%.

The building evacuation time for a fire very low in the building in the counterflow scenario will asymptote to the ‘closed stairwell’ scenario since the ascent time approaches zero. The percentage impact of counterflow on occupant evacuation time for a fire high in the building (where no occupants are forced to change stairwells) is similar for both stairwell configurations (two 1700 mm (66 in) and three 1100 mm (44 in) stairs) at 14 %; however, as the baseline occupant evacuation time for the three stair configuration is shorter than the baseline occupant evacuation time for the two stair configuration (119 min versus 141 min), the total impact is less for the three stair configuration.

Therefore, the rightmost two columns in Table 3 show the impact of emergency response when the calculations are normalized on a common basis (in this case, 179 min for two 1100 mm (44 in) stairs with no emergency response). Three 1100 mm (44 in) stairwells with emergency responders will result in faster occupant evacuation times than two 1100 mm (44 in) stairs without emergency responders (as shown by the negative values for evacuation times for three 1100 mm (44 in) stair rows in Table 3). Two 1700 mm (66 in) stairs with emergency responders will result in longer evacuation times than two 1100 mm (44 in) stairs without emergency responders, with the exception of the fire high in the building and firefighter counterflow scenario because there are no occupants above the fire floor when the firefighters arrive.

Emergency response strategy is a trade-off between minimizing the arrival time of the firefighters to the fire floor in order to conduct rescue and suppression activities and minimizing the occupant evacuation time. The strategy of closing a stairwell upon arrival of the fire department will approximately double the evacuation time if only two stairways are otherwise available (141 min with both 1700 mm (66 in) stairs available compared to 274 min if one stairwell is removed from occupant service after 10 min). If three stairways are available, the strategy of closing a stairwell will increase the occupant evacuation time by 46 % (119 min with three 1100 mm (44 in) stairs available compared to 174 min if one stairwell is removed from occupant service after 10 min). On the other hand, closing one stairwell can dramatically reduce the response time for the emergency responders for fires higher in the building; for a response to a fire on floor 50, it would take firefighters 129 min to reach the fire floor for a 1700 mm (66 in) stairway with counterflow versus 41 min for an open 66 in (1700 mm) stairway; 108 min for a 1100 mm (44 in) stairway with counterflow versus 41 min for an open 1100 mm (44 in) stairway.

If the counterflow strategy is employed by the firefighters, the impact of the occupants on firefighter response time is dependent upon the location of the fire in the building. For fires high in the building (floor 50), two 1700 mm (66 in) stairs require 19 % longer evacuation time (129 min versus 108 min) than three 1100 mm (44 in) stairs. For fires in the middle of the building (floor 25), two 1700 mm (66 in) stairs require 10 % greater evacuation time (67 versus 61 min) than three 1100 mm (44 in) stairs. For a fire on floor 5, no simulation was performed.

<u>Conclusions:</u>

Subject to the assumptions and limitations of this simplified analysis, it is apparent that if the fire department uses a stairwell (either by removing it from occupant use or walking upward against the flow of the occupants) for emergency response prior to completion of the evacuation, an additional stairwell restores all or more of the capacity lost to fire department suppression operations. Further, when comparing equivalent total width, additional stairwells outperform wider stairwells from the perspective of evacuation performance. No cost analysis was performed for this study.

Acknowledgments: The authors wish to acknowledge the contributions of Jessica Kratchman, Erica Kuligowski, and Richard Peacock, NIST.

---

[1] "Evacuation behaviors at exit in CA model with force essentials: A comparison with social force model." Song, W., Yu, Y., Wang, B., and Fan, W. Physica A, Vol. 371 (2006) pp. 658-666.
[2] "Emergency Responder Counterflow in Stairwells." Averill, J. and Kratchman, J. *Partners for Protection: Fire Protection Engineers and the Fire Service.* Oct. 17 and 18, 2006, Ellicott City, Md.