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Developing a database for emergency evacuation model

Long Shi*, Qiyuan Xie, Xudong Cheng, Long Chen, Yong Zhou, Ruifang Zhang

State Key Laboratory of Fire Science, University of Science and Technology of China, West Campus, Anhui, Hefei 230027, PR China

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A B S T R A C T

Performance-based design (PBD) has been playing an important function in fire safety of buildings, and how to accurately simulate occupants' behavior gains attention from fire engineers. With booming development of evacuation software, developing an extensive database for evacuation models is imperative and urgent. According to the literature, the whole process of evacuation includes several stages, such as pre-movement, action period, walking period, etc. In order to develop an evacuation model, data in these stages concerning pre-movement time, walking speed, occupant characteristics, actions and exit choice decisions are compiled in this paper. These data can be used as input parameters for evacuation models in PBD or in validating the evacuation models' accuracy.

1. Introduction

Evacuation plays an important role in performance-based design, and how to make simulation more accurate has significance for researchers and engineers. With the development of evacuation software, engineering applications are growing in number and are showing a powerful applicability.

For any evacuation software, data on occupants' behavior is urgently needed. Some software focuses on egress time but neglects other aspects such as pre-movement time and exit choice decisions. Therefore, a collection of these data may provide guidance for evacuation software. To collect evacuation data, many real fire events are used, for example, the World Trade Center [1,2]. However, the number of real fire events is limited. A large number of evacuation experiments have been carried out to gain data in different locations, such as high-rise apartments [3,4], large retail stores [5], ships [6], classrooms [7], public transport terminals [8], cinemas and th eaters [9]. Data on disabled occupants has also been collected in other experiments [9,10]. Generally, to develop an evacuation model there is a strong need to collect data on the following six aspects [12]:

- delay times, since people do not react instantaneously on becoming aware of an emergency;
- walking speeds, under a range of conditions of crowdedness, on horizontal surfaces, and up and down stairways;
- occupant characteristics, to account for differences in actions and reactions among the different types of people for different types of occupants;
- actions during evacuation, since they may increase the time people take to leave the building;
- effects of obstructions in travel paths, which can cause delays or block egress; and
- exit choice decisions, which determine travel paths and affect travel times.

Although obstructions in buildings have effects on travel paths, it is difficult to express these effects by data alone. Therefore these data are not included in this paper.

2. Pre-movement time

In BSI DD240, pre-movement time is defined as the time after an alarm or cue is evident but before the occupants of a building begin to move towards an exit. It comprises two components: recognition time and response time [5]. There is also another definition of pre-movement time: it is sometimes described as "initial response time" or "time to start", and it can be defined as the elapsed time from when an occupant perceives that something unusual is happening to the time this person decides to attempt to evacuate the building or to reach an area of refuge [12].

Data for delay time are various and there are a large number of influencing factors [5,13,14] upon it. Building type is one of these and can be classified by offices, shops and commercial places, public entertainment places, large retail stores, schools and hospitals. Data according to building type are listed in Table 1. Data

* Corresponding author. Tel.: +86 136 1560 0214; fax: +86 55 1360 6981.
E-mail address: shilong@mail.ustc.edu.cn (L. Shi).

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Table 1
Pre-evacuation time according to building type.

Building type			Mean pre-movement time (s)	Range	Count	References
Offices			113.4	0–540	19[a]	[13]
Shops and commercial places			108.6	0–420	16[a]	
Public entertainment places			120	0–540	28[a]	
Large retail stores	Foodhall		37.1	22.1–45.0	410	[5]
	Lingerie		22.3	18.0–29.0		
	Childrenswear		29.6	22.4–37.0		
	Household		27.1	19.3–34.8		
	Menswear		24.7	22.3–26.6		
	Ladies shoes		29.5	23.0–36.0		
	Ladieswear		29.3	18.2–45.6		
	Customer services		21.1	19.0–23.1		
School		Staff	70.8	0–246	17	[14]
		Student	73.7	8–200	228	
Hospital	Pathology and physiotherapy	Staff	52	26.0–91.0	9	
		Patients	37.3	30.0–45.0	3	
		All	48.3	26.0–91.0	12	
	Waiting room	Staff	26.0	16.0–43.0	4	
		Patients	36.3	34.0–40.0	4	
		All	31.1	16.0–43.0	8	
	Treatment	Staff	45.0	45.0–45.0	1	
		Patients	59.1	46.0–66.0	12	
		All	58.0	45.0–66.0	13	
	All areas	Staff	44.1	16.0–19.0	14	
		Patients	50.8	30.0–66.0	19	
		All	48.0	16.0–91.0	33	

[a] Denotes the number of fire events; the rest present the counting number of persons in experiments.

for larger retail stores and hospitals are listed by special areas in them. Pre-evacuation time in Table 1 from Ref. [13] was based on fire investigation, and the data in Table 1 for large retail stores were obtained by unannounced evacuation drill.

Other influencing factors [14,15] include the number of actions prior to evacuation, the level of prompting by people, the delay actions and the type of alarm system. The mean and standard deviation in Table 2 concerning delay actions had been selected to create a log-normal distribution between values that were considered likely to occur.

Data in Table 3 were gained from a series of experiments in different apartment buildings [16]. Those buildings were chosen because of their complexity of occupants, which included adults, children, seniors and people with disabilities. There were four buildings with different alarm systems. Building 1 was equipped with a two-stage fire alarm system, which sent out an alert signal (intermittent rings) that would sound all over the building and could be changed into a full fire alarm (continuous ringing) after 5 min. The other three buildings had single-stage central fire alarm systems with alarm bells located in corridors and staircases. The alarm bells in building 2 were recessed into the corridor walls. In building 3, the alarm bells were installed on the corridor walls. Building 4 had a complex architectural design, in which alarm bells were located only on the 4th and 6th floors, and in the staircases [16].

3. Walking speed

Walking speed is an important parameter used in evacuation models and varies with many factors, such as walking types [17], walking conditions [6], occupant types [18] and place types

Table 2
Pre-evacuation time according to influencing factors.

Factors		Mean pre-movement time (s)	Range	St. Dev.	Count (persons)	References
Number of prior actions	≤1	56.9	8.0–141.0	38.4	62	[14]
	2	71.0	14–167.0	31.6	121	
	≥3	104.0	17–200.0	34.4	41	
Level of prompting	Without prompting	64.8	10–200		119	
	Prompted by students	91.6	38–196		22	
	Prompted by member of staff	81.4	8–147		87	
Delay action	Notify others	10		3		[15]
	Call fire brigade	30		9		
	Inaction	60		18		
	Collect belongings	30		9		
	Telephoned others	30		9		
	Close/open doors/windows	5		1.5		
	Shut down equipment	20		6		
	Rescue	30		9		
	Got dressed	60		18		
	Woke up	60		18		

[19]. The walking speeds according to influencing factors are listed in Table 4. However, few experiments have covered walking speed when occupants are evacuated under special conditions, such as smoke concentration and traveling speed type.

In Table 5, according to Ref. [11], experiments on wheelchairs were carried out by individuals sitting in a wheelchair. The individual was moved by an aide in the season from spring to early summer when subjects were wearing just light clothing. It should be noticed that gender difference of walking velocity of wheelchair users was not found at a level of 5% significance.

Special travel speeds classified by slope gradient in Table 6 were acquired by Fruin [23], and other travel speeds on down-stairs could be obtained by interpolation. Regretfully, there was no information for travel speeds on up-stairs in this document.

Although few have studies mentioned spiral stairs, they have been popularly adopted in Sweden . A series of experiments on spiral stairs were conducted by Kvarnström [22] the subjects of which were students. As expected, the travel speeds on spiral stairs were slower than those on normal stairs. The slope gradient of two spiral stairs used in the experiment was 45° and stair radiuses were 65 cm and 85 cm, respectively. The walking route radiuses of these two stairs were 40 cm and 55 cm, respectively.

Table 3
Pre-evacuation time based on the type of alarm system [16].

Type of alarm system		Mean pre-movement time (s)	Details
Two-stage fire alarm system	1	150	Every department had a fire alarm bell inside the apartment
Single-stage central fire alarm systems	2	502	Located in corridors and staircases
	3	582	Installed on the corridor walls
	4	188	Located only on the 4th and 6th floors, and in the staircases

Table 4
Walking speed according to influencing factors.

Influencing factors		Speed (m/s)	Range (m/s)	References
Walking type	Free move		1.2–1.8	[17]
	Exit move		0.8–1.5	
Walking conditions for corridors, doorway on ship	Low	1.4		[6]
	Optimum	0.70		
	Moderate	0.39		
	crush	0.10		
Place type	Public place		0.51–1.27	[19]
	High-rise apartment	1.05	0.57–1.20	
		0.95	0.56–1.12	
Occupant type[a]	Children	1.08		[18]
	Female elderly	1.04		
	Male elderly	1.05		
	Elderly	1.04		
	Female adult	1.24		
	Male adult	1.30		
	Adult	1.27		

[a] The walking speeds according to occupant type are average data. All of these data were take when pedestrian density was less than 0.43 person/m^2.

Table 6
Travel speeds on stairs in terms of stair characteristics.

Stair characteristics			Speed (m/s)	Remarks	References
Stair dimensions	0.20; 0.25[a]		0.85		[22]
	0.18; 0.25		0.95		
	0.17; 0.30		1.00		
	0.17; 0.33		1.05		
	gradient	Up-stair	Down-stair		
Slope gradient	20°		0.9		[23]
	25°		0.8		
	30°		0.7		
	35°		0.6		
	40°		0.5		
	45°		0.4		
Spiral stair	Wide		0.55	Step height 0.15 ~ 0.21 m, step width 0.18 m, radius 0.85 m, walk radius 0.55 m	[22]
	Narrow		0.50	Step height 0.20 m, step width 0.21 m, radius 0.65 m, walk radius 0.4 m	

[a] The first data are step height and the second are step width; also, the speed data are the maximal travel speeds.

Table 7 shows travel speeds on stairs with different occupant densities [22]. The experiment was taken on a 32° gradient stair, whose step height and width were 0.17 and 0.27 m, respectively. The distance between rods was 1.34 m and the distance from wall to rod was 7.5 cm. In Table 7, the data from Ref. [22] are random, explaining why there are two travel speeds for the same occupant density.

The travel speeds on stairs in high- rise buildings in Table 8 were collected through fire drills [20,21]. It was found that the differences of speed between up-stairs and down-stairs for crutches, walking stick and no disability are small. Data for different disabled subjects are collected from referenced literature and the missing data are not recorded in the original publications.

4. Occupant characteristics

A large number of factors can have an effect on evacuation [25], all of which can be simply classified into occupant characteristics, building characteristics and fire characteristics. Besides these three characteristics, many factors are also divided into several aspects. Building characteristics, for example, can be classified by occupant types, architecture characteristics, activities type, activities in the building and fire safety features. Details about these factors are listed in Table 9.

5. Actions during evacuation

The research on human behavior can be divided into four phases [26]: phase 1 commenced in 1956 with work by Bryan [27] which

Table 5
Walking speed for disabled occupants.

Factors		Speed (m/s)	Range (m/s)	References
Wheelchair	Man	1.06		[11]
	Woman	1.06		
High-rise building	Electric wheelchair	0.89		[20]
	Manual wheelchair	0.69		
	Crutches	0.94		
	Walking stick	0.81		
	No disability	1.24		
Disabled subjects	All disabled subjects	1.00	0.10–1.77	[21]
	With locomotion	0.80	0.10–1.68	
	No aid	0.95	0.24–1.68	
	Crutches	0.94	0.63–1.35	
	Cane	0.81	0.26–1.60	
	Walker/Rollator	0.57	0.10–1.02	
	Without locomotion disability	1.25	0.82–1.77	
	Unassisted wheelchair	0.89	0.85–0.83	
	Assisted ambulant	0.78	0.21–1.40	
	Assisted wheelchair	1.30	0.84–1.98	

Table 7
Travel speeds on stair according to occupant.

Influencing factors			Speed (m/s)		References
			Up-stairs	Down-stair	
Occupant density (persons/m^{-2})		One by one		1.0	[22]
		2.5		0.88	
		2.4		0.82	
		2.2		0.91	
		1.5	0.57		
		1.5	0.76		
		2.0	0.72		
		One by one	0.8		
Conditions for traveling on ships		Low	0.80	1.00	[6]
		Optimum	0.40	0.50	
		Moderate	0.22	0.28	
		Crush	0.10	0.13	
Occupant age	Male	<30	0.67	1.01	[24]
		30–50	0.63	0.86	
		>50	0.51	0.67	
	Female	<30	0.635	0.755	
		30–50	0.59	0.655	
		>50	0.485	0.595	
Occupant type[a]	Children		0.29	0.31	[18]
	Female elderly		0.27	0.26	
	Male elderly		0.29	0.29	
	Elderly		0.28	0.28	
	Female adult		0.30	0.36	
	Male adult		0.32	0.42	
	Adult		0.31	0.38	

[a] The travel speeds on stairs according to occupant type are average data. All of these data were take when pedestrian density was less than 0.72 person/m^2.

Table 8
Travel speeds on stair for disabled occupants.

Influencing factors		Speed (m/s)		References
		Up-stairs	Down-stairs	
High-rise building	Crutches	0.22	0.22	[20]
	Walking stick	0.32	0.34	
	No disability	0.70	0.70	
Disabled subjects	All disabled subjects	0.62 (0.21–1.32)[a]	0.60 (0.10–1.83)	[21]
	With locomotion	0.59 (0.21–1.08)	0.58 (0.10–1.22)	
	No aid	0.68 (0.30–1.08)	0.68 (0.28–1.22)	
	Crutches	0.46 (0.35–0.53)	0.47 (0.42–0.53)	
	Cane	0.52 (0.21–1.05)	0.51 (0.18–1.04)	
	Walker/Rollator	0.35 (0.30–0.42)	0.36 (0.10–0.52)	
	Without locomotion disability	1.01 (0.70–1.32)	1.26 (0.70–1.83)	
	Unassisted wheelchair	(0.70–)	(1.05–)	
	Assisted ambulant	0.53 (0.23–0.72)	0.69 (0.42–1.05)	
	Assisted wheelchair	0.89 (0.53–1.05)	0.96 (0.70–1.05)	

[a] Data before parentheses are the mean travel speed on stair. The former and latter data in parentheses are the minimal and maximal travel speed on stairs, respectively.

Table 9
Factors effecting human behavior in fire [25].

Occupant characteristics	Building characteristics	Fire characteristics
Profile	**Occupancy**	**Visual cues**
• Gender	Residential (lowrise, midrise, highrise)	Flame
• Age	Office	Smoke (color, thickness)
• Ability	Factory	Deflection of wall, ceiling, floor
• Limitation	Hospital Hotel Cinema College and University Shopping Centre	
Knowledge and experience	**Architecture**	**Olfactory cues**
• Familiarity with the building • Past fire experience • Fire safety training • Other emergency training	• Number of floors • Floor area • Location of exits • Location of stairwells • Complexity of space/finding way • Building shape • Visual access	• Smell of burning • Acrid smell
Condition at the time of event	**Activities in the building**	**Audible cues**
• Alone vs. with others • Active vs. passive • Alert • Under drug/alcohol/medication	• Working • Sleeping • Eating • Shopping • Watching a show, a play, a film, etc	• Cracking • Broken glass • Object falling
Personality	**Fire safety features**	**Other cues**
• Influenced by others	• Fire alarm signal (type, audibility, location, number of nuisance alarms)	• Heat
• Leadership	• Voice communication system	
• Negative toward authority • Anxious	• Fire safety plan • Trained staff • Refuge area	
Role • Visitor • Employee • Owner		

Table 10
Occupant statistic of Fire cues in residence [34].

Fire cues	Occupant percent	Occupant account
Smell of smoke	26.0	148
Told by others	21.3	121
Noise	18.6	106
Told by family members	13.4	76
Notice smoke	9.1	52
Notice flame	8.1	46
Explode	1.1	6
Feel heat	0.7	4
Fire bridge	0.7	4
Electricity breaking	0.7	4
Observation of pets	0.3	2

was followed in 1972 by *The Behavior of People in Fires* study by Woods [28]; the second phase in the development of human behavior in fire was characterized by major programs of research and international seminars held in the United States [29] and the United Kingdom [30]; the third phase saw major contributions from Sime [31] and Bryan [32] together with reports on major fire incidents characterized by large loss of life. Phase 4, according to Pauls, started with the First International Symposium on Human Behavior in Fire in Belfast in 1998 [33].

Fire cues in fire scenarios are various and will lead to different response times and cause distinct results. Some deaths happened because the occupants did not know the coming danger or took a long time to respond. In this way, investigating fire cues is very important to fire safety because these kinds of messages can provide the occupants' response time and help to take measures to reduce it. Table 10 shows fire cues according to Bryan [34]; and it is necessary to note that noise includes not only the noise produced by evacuation but other noise relevant to fire development.

Data in Table 11 were provided from questionnaires in four large retail stores [5]. It is recognized that the cues are not mutually exclusive but may occur in a sequential fashion. As shown in Table 11, it is noted that informed by staff and hearing the alarm, which account for over 80%, were the two main cues when fire happened in large retail stores.

Table 12 gives the differences of first responses between American males and females in fire events [34]. It is noted that the differences of first response, such as finding fire source, helping family members to evacuate, evacuating the building, and calling fire brigade, are distinct.

The percentages of fire behaviors in large retail stores in Table 13 were the mean values of four different larger stores, which included three-storey city center stores and single-storey out-of-town stores in different locations in the United Kingdom [5].

From Table 14, of the customers who entered the premises accompanied by others, 14.5–19.3% occupants in these four stores were separated when the alarm sounded [5]. Of the customers who had separated on entering the stores, approximately 28.6– 50.0% of occupants searched for, found and rejoined their companions before evacuating.

Table 11
Emergency cues in large retail stores [5].

Fire cues	Occupant percent	Range
Alarm	33.0	30.4–38.0
Told by staff	49.9	45.3–52.5
Others moving towards exits	14.4	10.8–20.8
Followed companions	1.3	0.0–2.8
Told by other shoppers	1.3	0.0–3.2

Table 12
Differences between male and female for the first response in fire events [34].

Behavior	Percent		Behavior	Percent	
	Male	Female		Male	Female
Notify others	16.3	13.8	Go to fire area	1.9	2.2
Find fire resource	14.9	6.3	Move fire materials	1.1	2.2
Call fire bridge	6.1	11.4	Entering building	2.3	0.9
Got dressed	5.8	10.1	Try to through exit	1.5	1.6
Evacuate from building	4.2	10.4	Go to fire alarm place	1.1	1.9
Help family members to evacuate	3.4	11.0	Notify others by phone	0.8	1.6
Fire fighting	5.8	3.8	Try to fight fire	1.9	0.6
Search for fire extinguisher	6.9	2.8	Close the door of fire area	0.8	1.3
Evacuate from fire area	4.6	4.1	Sound fire alarm system	1.1	0.6
Wake up	3.8	2.5	Shout down equipment	0.8	0.9
Inaction	2.7	2.8	Check pats	0.8	0.9
Let other to call fire bridge	3.4	1.3	Anything else	6.5	2.5
Collect belongs	1.5	2.5			

6. Exit choice decisions

Information on exit choice gained by video tapes in four large retail stores is listed in Table 15 [5]. The number of occupants who chose familiar exits and emergency exits are almost the same. The reasons for exit choice were obtained from questionnaires. It is noted that most of the customers choose the nearest exits.

7. Discussion and conclusions

According to the literature reviewed, the mean pre-movement times according to building type were not longer than 120 s. The pre-movement times ranging from 0 to 540 s were collected from fire events in which there were various kinds of occupants. Considering the mean pre-movement time in different types of buildings, it is found that the mean pre-movement time of occupants decreases in the order public entertainment places, offices, shops and commercial places, schools, hospitals and large retail stores . Within these, the differences among offices, shops and commercial places, public entertainment places are not distinct.

According to the experiments carried out in apartment buildings, it is known that the alarm system has a paramount influence on the pre-movement times, which range from 150 to 582 s. The minimum time occurred when two-stage fire alarm systems were installed inside every apartment and the maximum was recorded when single-stage central fire alarm systems were installed on the corridor walls.

Walking speeds differ according to walking types, walking conditions, place types and occupant types. There is an extensive range of walking speed from 0.1 to 1.8 m/s. The range of walking speed for the disabled ranges from 0.1 to 1.98 m/s and the maximum is larger than that of normal occupants because of wheelchair assistance.

Travel speed on stairs could be divided into two situations: up-stair and down-stair. As shown in literature, travel speeds down-stair are slightly quicker than those up-stair, but the difference is not so obvious. Generally, travel speeds on stairs range from 0.4 to 1.05 m/s. The minimum occurred when the gradient of down-stair is 45°. The maximum occurred when the height and width of steps were 0.17 m and 0.33 m, respectively. Similar to the situation of walking speed, the range of travel speeds of disabled occupants on stairs, which ranges from 0.1 to 1.83 m/s, is wider than that of normal occupants.

The proportions of fire cues vary among building types. The three most important fire cues in residences, which account for 65.9% of all the cues, are smell of smoke, warnings from others, and noises. In large retail stores with a dense crowd, the primary fire cues were warnings from staff and the alarm sound, which account for up to 82.9%.

Based on an average estimation of total percentage of residential occupants' behaviors, it is found that getting dressed, calling the fire brigade and notifying others comprise the three biggest proportions. Differences of first response between males and females also exist in fire events. It is noted that the gender differences in finding the fire source, helping family members to evacuate, evacuation from building and calling the fire brigade are distinct and larger than 5.0%. In those four first responses, the percentage of each first response for females is larger than that for males except for finding the fire source.

From the questionnaires concerning the reason for exit choice in the experimental scenario of large retail stores, 50.1% of occupants chose the nearest exit while 19.5% preferred to take familiar exits instead; but during the real evacuation drill, choosing the familiar exits reached 54.7% while 45.3% of occupants chose emergency exits.

Table 13
Occupant behaviors in fire events.

Influencing factors		Percent	Account (persons)	References
Fire behavior in large retail stores	Entering	7.8	983	[5]
	Walking through store	8.0		
	Browsing	32.4		
	Changing	3.1		
	Choosing goods	38.8		
	Queuing	9.4		
	Purchasing	7.4		
	Exiting	3.1		
Average estimate of total percentages of occupants' behaviors	Notify others	25.3		[15]
	Investigate/search for fire	12.1		
	Call fire brigade	32.8		
	Inaction	11.8		
	Collect belongings	12.6		
	Telephoned others	5.1		
	Close/open doors/windows	9.3		
	Shut down equipment	1.5		
	Rescue	12.4		
	Got dressed	48.5		
	Woke up	3.8		

Table 14
Status and primary actions at alarm of customers accompanied by others on entering the store [5].

Status	Mean occupant percent	Range
Together at alarm	83.5	80.7–85.5
Separated at alarm	16.5	14.5–19.3
Searched for and left with friends	35.1[a]	28.6–50.0

[a] The data denote as percentage of those separated.

Table 15
Choosing exit in fire events in large retail stores [5].

Influencing factors		Percent	Range
Exit type	Familiar	54.7	19.7–71.8
	Emergency	45.3	28.2–80.2
Reasons for exit choice	Familiar exit	19.5	14.6–29.7
	Nearest exit	50.1	29.7–69.9
	Directed to by staff	25.2	13.4–32.6
	Followed others/directed by others	5.2	0.4–9.5

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