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Pedestrian Flow Characteristics on Stairways During Disaster Evacuation

C. J. KHISTY

ABSTRACT

Although the design and operation of pedestrian facilities in disaster situations are much more critical than they are under everyday, normal conditions, comparatively little research has been done on people movement during disasters. A preliminary investigation of the nature of pedestrian movement on stairways in high-rise residential buildings under emergency or disaster conditions is described. Such people movement down stairways is the most crucial activity in cases of fire. It was found that current codes and regulations in regard to personal space, speed, and flow of people using stairways under emergency or disaster conditions are in need of revision. Recommendations based on the results of this study are made for designing safe stairways and for developing building code requirements. The findings can also be applied in designing stairways in stadiums, theaters, arenas, and other public facilities where stairways are a part of the pedestrian circulation system.

The movement of people down stairways of high-rise buildings is by far the most crucial activity in cases of fire. Comparatively little research has been done on people movement on stairways during emergency or disaster conditions although such movement under everyday, normal conditions has been extensively researched and documented during the last two decades (1-3). Ironically, many of the results of studies in nondisaster or nonevacuation contexts have been applied in developing building code requirements for means of egress in disaster situations (4). Because the design and operation of facilities for pedestrians under disaster conditions are generally much more critical than they are under nondisaster conditions, there is a need to investigate human behavior and movement characteristics under the former situation.

The purpose of this research is two-fold: first, to investigate human behavior under disaster conditions, such as the human response to fire, and second, to investigate pedestrian movement with respect to flow, speeds, and densities on one of the most critical links of pedestrian circulation, stairways of buildings, under disaster conditions.

Current research on pedestrian flows on stairways in high-rise residential buildings during evacuation under simulated emergency conditions is described. The results of this investigation are compared with similar findings from current literature. Recommendations based on the results of this study are made for design and operational considerations. The findings may also be helpful in designing stairways for pedestrian facilities in nonemergency contexts.

BACKGROUND

Some long-standing myths about how people behave in emergency conditions caused by natural disasters are being increasingly challenged. Recent research indicates that human behavior can be rational in emergencies and that panic rarely occurs during disasters (5). Although this may sound optimistic, there are reports that point out that immediate, rapid, well-organized evacuation of tall buildings and public places under emergency conditions appears to be the exception rather than the rule (6). Also, recent research indicates that there is a tendency to oversimplify design assumptions and the dynamics of pedestrian flow in emergency planning (4). Pauls (4) reports that even in simple evacuation drills the evacuation times observed were about twice as long as had been originally predicted.

Obviously, the current state of knowledge concerning human behavior and performance during disasters needs to be expanded. The development of building codes, standards, and criteria for designing stairs should take into consideration not only those attributes of human performance under everyday, normal conditions, but also attributes under emergency conditions. The pioneer work of Wood (7) and Pauls (4) has encouraged researchers to assess human behavior in fire emergencies and has helped to dispel inaccurate ideas of how people behave under such conditions.

STUDY DESCRIPTION AND MEASUREMENT TECHNIQUES

The main objective of this study was to investigate pedestrian flow characteristics on stairways of high-rise buildings in response to fire. Although there were no opportunities to observe these characteristics during an actual fire, the investigation was done under simulated emergency evacuation conditions with the assumption that the behavior of evacuees would be similar in real fire emergencies. During 1983-1984, a total of 21 test evacuations

were observed in dormitory buildings ranging between 3 and 12 stories in height on the campus of Washington State University (WSU), Pullman, Washington. WSU's Fire Safety Department usually conducts two fire emergency drills per year for each dormitory. Drills were conducted without warning and under simulated fire conditions.

Pedestrian flow can be described in terms of speed and density (concentration):

$$q = kv$$

where

q = pedestrian flow volume in pedestrians per foot-width of stairway per minute,

v = pedestrian space mean speed in feet per minute, and

k = pedestrians per square foot of stairway (density or concentration).

Time-lapse photography, at 18 frames per second, was used to film the movement of people on the stairways. A camera speed of 2 frames per second would have been adequate, but the equipment available necessitated using 18 frames per second. Filming was done on 15-m super-8 rolls. The analysis of the film was done using a hand-operated editing machine. All timing measurements were initially made in frames and subsequently converted to real time. Pedestrian speeds were obtained from the films by recording the time taken by subject pedestrians to cross two or more specified points on the stairways. Similarly, the corresponding pedestrian densities were obtained by counting the number of pedestrians within a specified area. When the individual speeds (v ft/min) and corresponding densities (k peds/ft²) for subject pedestrians had been calculated, the corresponding flows (q peds/ft/min) were obtained from the relationship $q = kv$.

Between 3 and 15 observers were engaged in recording information and gathering data on evacuation movements depending on the size and height of the building. Portable tape recorders, stop watches, and still cameras were used to record observations. Observers generally moved along with evacuees from floor to floor and were able to collect data unobtrusively.

After the fire drills were over, a random interview of approximately 10 percent of the evacuees revealed that about 80 percent of those interviewed believed that the building evacuation was indeed in response to a genuine fire. About 99 percent of the dormitory occupants were students between the ages of 18 and 30. The stairways in the 21 dormitory buildings observed have the following general characteristics:

1. Almost all the stairways have scissors configurations (19 out of 21).
2. The risers are between 6 1/2 and 7 1/2 in. high.
3. The treads are between 11 and 12 in. wide.
4. The width of stairways varied between 4 and 7 ft.
5. All stairways have handrails.
6. The evacuation exercises were done at all hours of the day and as late as 11 p.m. Fifty percent of the exercises were during the spring and fall and 50 percent during the winter.

EVACUATION OBSERVATIONS AND RESULTS

The movement of people down passages, ramps, and stairways of buildings is by far the main physical

activity in case of fire. The collection of data for such variables as spacing, density, speed, flow, queuing, and evacuation time was considered the most crucial part of this study. Observations were confined to stairways only.

This study was essentially done in two phases. Phase 1 consisted of collecting data under normal circumstances, which included peak and off-peak flows, when there was no threat of fire, and Phase 2 consisted of collecting similar data under fire emergency circumstances. It must be noted that under normal circumstances people were using the stairs as well as the elevators wherever the latter were available. Under fire emergency conditions, of course, the elevators were not operational, and hence everybody was forced to use the stairways. A total of 200 valid samples were recorded in each phase. Details regarding personal space, speeds, and flows of evacuees follow.

Personal Space

Table 1 gives the frequency distribution of horizontal stairway area occupied per person under emergency (fire) conditions and also under normal, everyday conditions. Figure 1 shows these data graphically. Under fire emergency conditions the mode and median of person occupancy were 5.5 and 7.7 ft² per per-

TABLE 1 Frequency Distribution of Person Occupancy on Stairways

Pedestrian Occupancy (ft ² /person)	Frequency Under	
	Emergency Conditions	Normal Conditions
3.5	5	1
4.5	22	6
5.5	23	20
6.5	36	42
7.5	33	40
8.5	20	22
9.5	10	20
10.5	10	17
11.5	6	12
12.5	6	5
13.5	7	6
14.5	7	2
15.5	3	2
16.5	4	2
17.5	3	1
18.5	3	1
19.5	2	1
Total	200	200

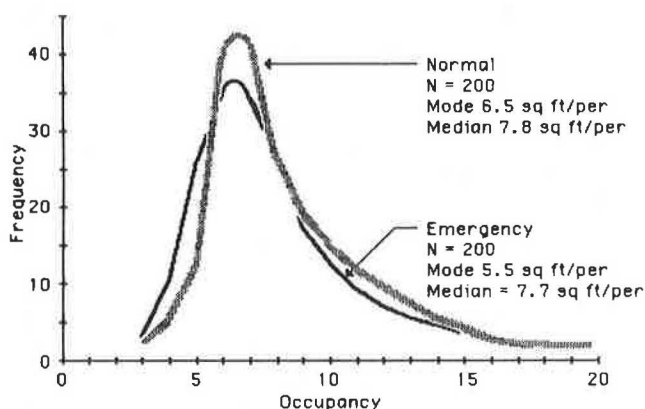


FIGURE 1 Personal space.

son, respectively. In comparison, the mode and median of person occupancy under normal conditions were 6.5 and 7.8 ft² per person, respectively. Note that there was an increase of about 80 percent in the number of persons occupying a space of 5 ft² or less in case of an emergency compared with the normal situation.

Speeds and Flows

The data given in Table 2 indicate the densities, speeds, and flows of pedestrians down the stairways under normal and fire emergency conditions. A maximum flow of 16.42 pedestrians per minute per foot-width was observed under normal conditions and a flow of 18.25 pedestrians per minute per foot-width was observed under fire emergency conditions. The highest density observed was about 0.29 pedestrians per square foot. In general, densities were found to increase in the lower stories of buildings. Figures 2 and 3 show these data graphically.

The highest speeds observed were 125 ft per minute and 137 ft per minute under normal and fire emergency conditions, respectively. Differences in the width of the stairways did not appear to cause changes in speeds or flows. Minor localized constrictions also had no apparent effect on speeds or flows.

Observations made during the emergency evacuations revealed that daytime evacuation exercises appeared to be carried out with less confusion than nighttime evacuations. Also, it appeared that, particularly at night and in spite of proper illumination, some crowding conditions on the stairways and passages tended to create hazardous conditions when occupancies were 3.5 ft² per person and less. It was also observed that nighttime evacuations created crowded conditions near the building exits at ground level and therefore choked the flow of evacuees trying to get out of the buildings. This situation could be hazardous in a real fire.

Cases of people tripping and falling on the stairways were rare. Such cases were confined to stairs that had riser heights of 7 1/2 to 8 in. and tread widths of 10 in. When a person tripped and fell, recovery was exceptionally fast.

Queuing at the entrance of stairways was observed in 25 percent of the evacuations, particularly in the lower stories of buildings, and lasted for a maximum of 25 sec. Most queues lasted for 5 sec and less. There were no apparent disruptions in evacuations due to queue formation.

No cases of fatigue were observed or reported during the exercises. It is reported that fatigue becomes a significant factor with severe adverse effects on people movement when evacuations down stairs exceed 5 min (8).

Some caution must be applied in interpreting and using the results because of the following factors:

1. These are preliminary findings based on a limited sample size.
2. The results are derived from simulated fire emergency exercises. These exercises were carried out without warning and therefore represent almost real conditions. A large majority of the evacuees interpreted the alarm and exercise as a genuine emergency.
3. Because the exercises were simulated there were no problems created by smoke and fumes. In a real fire, smoke and fumes would inhibit movement of stairway users and thereby reduce the capability of people to attain the speeds and concentrations indicated.
4. High-rise buildings with a range of configurations and characteristics were observed. There

TABLE 2 Pedestrian Movement Characteristics on Stairways

Occupancy, 1/k (ft ² /person)	Density, k (persons/ft ²)	Speed (ft/min)		Flow (person/min/ft-width)	
		Emergency, V_E^a	Normal, V_N^b	Emergency, q_E^c	Normal q_N^d
3.5	0.29	55	50	16.0	14.5
4.5	0.22	82	72	18.0	15.8
5.5	0.18	100	90	18.0	16.2
6.5	0.15	110	92	16.5	13.8
7.5	0.13	115	110	15.0	14.3
8.5	0.12	124	115	14.9	13.8
9.5	0.11	127	120	14.0	13.2
10.5	0.10	137	125	13.7	12.5
11.5	0.09	137	125	12.3	11.3
12.5	0.09	137	125	11.0	10.0
13.5	0.07	137	125	9.5	8.75

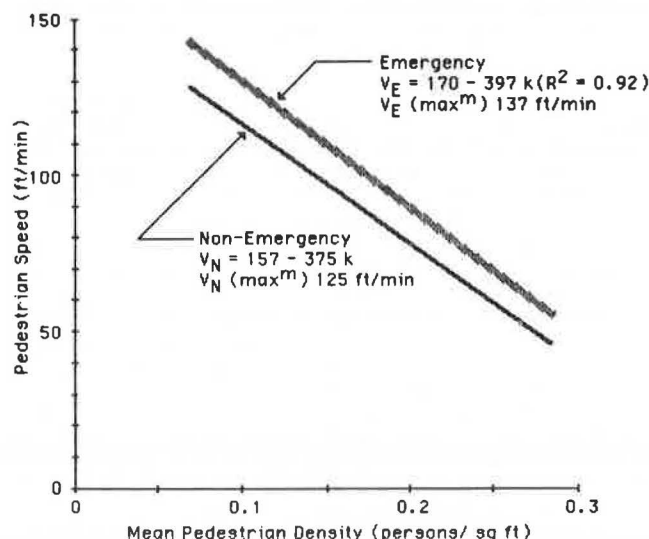
^a $\bar{V}_E = 114.6$, $S = 26.6$, and $f_E = 178$.^b $\bar{V}_N = 104.5$, $S = 25.4$, and $f_N = 191$.^c $\bar{q}_E = 14.5$, $S = 2.7$, and $f_E = 178$.^d $\bar{q}_N = 13.10$, $D = 2.3$ and $f_N = 191$.

FIGURE 2 Speed/density.

were variations in landing widths, stair widths, tread-to-rise ratios, and egress routes. Added to this were social factors such as communication levels, social organization, and leadership qualities of fire safety officers and evacuees. These latter factors, although difficult to measure, should not be overlooked.

5. All of the evacuees were between the ages of 18 and 30. None of them were handicapped.

DISCUSSION OF RESULTS

A summary of results obtained from this study is compared with the findings of other researchers in Table 3. Pauls' work is of particular interest because of the extensive data base he used (4). His results appear to be compatible with those of this study. Galbreath's data and results on the relationship between concentration of people on stairs and forward movement appear to be rather overoptimistic (9). Fruin's results are for normal conditions and have been inserted in the table for quick comparison (2).

The London Transport Board (LTB) (10) determined,

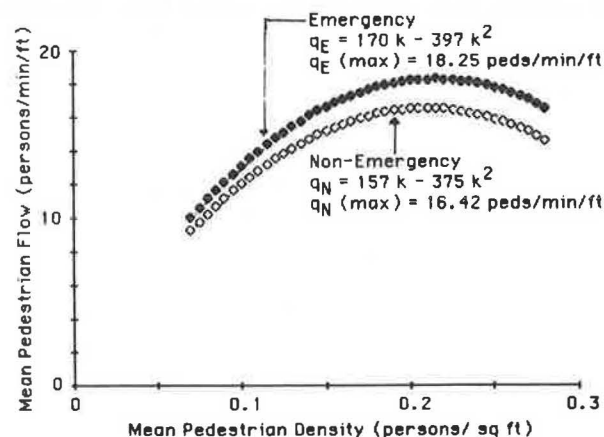


FIGURE 3 Flow/density.

under normal conditions, that the flow rate of passengers in level passages (4 ft and wider) is 27 persons per minute per foot-width, and the flow down stairways was determined to be 21 persons per minute per foot-width. These values appear to be somewhat high. The LTB document also reports that maximum flows on stairways occur when personal space is 3 ft² per person. In comparison, the results obtained from this study indicate that the maximum flow of 18.25 persons per minute per foot-width occurs at an occupancy of about 5 ft² per person under fire emergency conditions; the corresponding figures for normal conditions are 16.2 persons per minute per foot-width at about 5 ft² per person.

From the literature on disaster and fire safety it is evident that the 22-in. unit (or module) has frequently been used for determining stairway and exit widths. Indeed building codes across the country have in general been greatly influenced by the 22-in. unit. It is therefore not surprising to notice the flow rate of evacuees specified traditionally in terms of the 22-in.-width-per-minute unit.

Pauls' remarks in connection with his Ottawa observations that "the 22 inch width concept cannot be justified on the basis of fairly discrete lanes of movement, as previously believed. In addition the conventionally accepted flow of 45 persons per min per 22 inch of stairway width appears to be overoptimistic by 50 to 100 percent or more, especially

TABLE 3 Comparison of Pedestrian Movement Characteristics

Condition	Researcher				
	Khisty		Pauls, Fire	Galbreath, Fire	Fruin, Normal
	Normal	Fire			
Speed (ft/min) max ^m	125	137	100-140	158	128
Space (ft ² /person)					
Min ^m	3.5	3.0	3.5	2.5	— ^a
Mode	6.5	5.5	6.5		
Median	7.8	7.7	7.4		
Flow (ft/min/ft-width) Max ^m	16.42	18.25	16.36	23.45	20

^aLevel of service F, 4 ft² or less.

for mid-winter total evacuations in cold climates" (4). The "accepted flow" of 45 persons per minute per 22 in. of stairway is equivalent to 24.6 persons per minute per foot-width, which is at least 34 percent higher than the maximum flow observed in this study (4).

The "standard" unit (22 in.) for stairway and exit width has evidently been derived from the clearance width of adults. However, the width needed for walking adults is about 28 in. to account for body sway (8). "Body sway has been observed to range 1 1/2 inch left and right during normal free movement, and when movement is reduced to a shuffle in dense crowds and movement on stairs, a sway range of almost 4 inch has been observed. In theory this indicates that a width of 30 inch would be required to accommodate a single file of pedestrians traveling up or down stairs" (11).

The Life Safety Code developed by the National Fire Protection Association "is widely used as a guide to good practice and as a basis for laws or regulations. The code specifies the 'exit' in an overall definition of means of egress, and exits are measured in units of 22 inch width, taken from the average width of a man at shoulder height." In response to recent research on stairs "during both staged and normal evacuations the concept of a 30 inch width has been advocated" (11).

In a summary of life safety code provisions for occupant load and capacity of exits (Table 4) the number of persons per unit of stairs varies from 22 persons per unit width in hospitals to 75 persons per unit width in places of assembly. For residential buildings, such as dormitories, the capacity is 75 persons per unit width. This capacity translates to 41 persons per minute per foot-width and 30 persons per minute per foot-width if the unit width is taken as 22 and 30 in., respectively. These figures are 127 and 66 percent higher than observations made in this study and by Pauls (4). More recent work done by Pauls indicates peak flows of 30 persons per

minute and mean flows of 24 persons per minute per unit of exit width down stairways (12,13). Egan gives several references (8,pp.185-187) in which the unit width is taken as 22 in., which results in person flows far exceeding actual observations.

This is a matter of serious concern and needs to be examined carefully in light of ongoing research.

APPLICATIONS OF RESEARCH RESULTS

Some important research results of this study are

1. The traditional 22-in. width unit used in stairway design should be replaced by a performance-based width such as persons per minute per foot-width or persons per minute per meter-width.

2. A maximum pedestrian flow rate of 18 pedestrians per minute per foot-width should be allowed with space occupancies not less than about 5 ft² per person. An occupancy of 7.5 ft² per person is recommended.

3. Stairways must be wide enough for two people to descend side by side, thus improving the flow. This arrangement will help evacuate the aged or the infirm. The minimum width would be about 60 in. If a module is used at all, a 30-in. width per person is suggested.

4. Tread and riser dimensions should be uniform throughout the stairway. A minimum tread width of 11 in. (without nosing) and a maximum riser height of 7 in. are recommended.

5. Communication between fire control personnel and evacuees is important. Successful evacuation is heavily dependent on the use of a proper public address system that has the capability of conveying clear, audible messages.

Suggestions and recommendations for stairway design are in need of change as a result of studies done in recent years. The results provided in this paper can be transferred to stairways in theaters, arenas, stadiums, and other public buildings where stairways are a part of the pedestrian system.

SUMMARY AND CONCLUSION

This investigation consisted of measuring the personal space, speed, and flow of people descending stairways under two conditions, emergencies and normal everyday conditions. Observations were also made of the behavior of people during emergency conditions. It was found that current codes and regulations that address personal space and movement of people under emergency conditions are in need of revision, particularly because the design and operation of pedestrian facilities under disaster conditions are much more critical than they are under

TABLE 4 Summary of Life Safety Code Provisions for Occupant Load and Capacity^a

Type of Establishment	Capacity of Stairs (no. of persons per unit width)
Places of assembly	75
Educational	60
Health care	22
Residential	75
Mercantile	60
Business	60
Industrial	60

^aExtracted from Table 6-2c in Byran (11).

everyday, normal conditions. This investigation is justified on the basis of improving the development of safety regulations and design competence affecting the safety of human beings using stairways.

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Seattle Area HOV Lanes: Innovations in Enforcement and Eligibility

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ABSTRACT

Preferential high occupancy vehicle facilities such as lanes restricted for transit and carpools are playing an increasingly important role in urban transportation systems. The preferential treatment poses, however, new operational problems for state and local transportation departments and enforcement officials. The minimum occupancy requirement for carpools must be set and effective enforcement of the facility must be maintained. A demonstration project in Seattle, Washington, tested the use of a public telephone hotline to reduce transit and carpool lane violations and also introduced the use of a variable carpool definition in order to maximize transit and carpool lane effectiveness. The variable carpool definition was tested by lowering the occupancy requirements from three to two persons per vehicle at selected locations in an Interstate corridor. Project data showed a 33 percent reduction in transit and carpool violation rates attributable to the public hotline. The change in carpool definition occurred smoothly. Vehicle volumes increased at locations where the occupancy requirement was lowered. Violation rates did not increase at locations where the requirement remained at three or more persons per vehicle. The key to the success of both elements of the project was an extensive, well-orchestrated public information campaign.