SELECTION 2

Calculation Methods for Egress Prediction

Rita F. Fahy

This selection, reprinted from the 2003 edition of NFPA's Fire Protection Handbook, *offers information and statistics for planning how people will react when faced with an emergency fire situation. All internal cross references, figure numbers, and table numbers remain unchanged and refer to the original published material.*

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CHAPTER 2

SECTION 4

Calculation Methods for Egress Prediction

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The evaluation of an engineered design requires a balanced comparison of predicted fire conditions and realistic evacuation predictions. Over the past several years, fire safety engineers have worked with, and developed confidence in, a range of calculation methods for the prediction of fire conditions. Researchers working in the area of human behavior in fire have begun to make real progress in recent years in the collection of data necessary for this analysis and in the development of predictive tools that will be comparable to those used to predict the growth and spread of fire and its effects.

Performance building and fire codes allow designers to use innovative building materials and concepts often not encouraged or even permitted in existing prescriptive codes, which can result in more cost-effective and creative designs. But this openness to innovation requires the designer to then demonstrate that the design is safe. For a design to be shown to be "safe," the designer must demonstrate that the time needed to move people to a safe location will be less than the time predicted when fire effects will have a potentially lethal impact on any occupant.

Time available to escape > Time needed to escape

Fire safety design is a two-sided problem that requires fire safety engineers and the enforcement community to have knowledge in the use of both fire models and egress and human behavior models. Currently, fire safety engineers are very well trained in predicting fire growth and the spread of fire effluents in a structure. The focus of a fire safety design appears to favor this component of the fire safety problem. But it is crucial that the complexity and importance of the egress/behavior component never be underestimated or short-changed and that a balance between both components be maintained.

For their part, building and fire officials (the enforcement community) will need to evaluate designs presented in their jurisdictions that will use various computer models or other calculation methods to demonstrate both the time necessary and the time available for occupant evacuation. They may need guidance on how to judge the appropriateness of methods, data, and assumptions used in these evaluations, particularly in the egress portion of analyses.

Members of both user groups must balance the two sets of escape time calculations in order to produce a meaningful result.

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COMPONENTS OF EVACUATION TIME

The evacuation time for an individual is the entire span of time that elapses from the ignition of the fire until the occupant emerges from the building or arrives at a location of safety. It consists of four components, all of which must be taken into consideration:

- Time to notification
- Reaction time
- Preevacuation activity time
- Travel or movement time

The first three components are often grouped together and referred to as "delay time" or "premovement time."

Evacuation time = Delay time + Travel time
= Time to notification + Reaction time
+ Preevacuation activity time
+ Travel time

It is very important that engineers not underestimate the contribution that delay time can make to total evacuation time. Studies of evacuation drills in apartment buildings have shown that, on average, travel time makes up less than 25 percent of the average total time to evacuate.[1] In office evacuations, however, delay times can be extremely short, and the largest proportion of total evacuation time is accounted for by travel time. Therefore, the selection, estimation, or calculation of premovement times is extremely important to obtain valid results.

Time to Notification

In the evaluation of an engineered building design, evacuation time begins when ignition occurs. Some period of time, the time to notification, will elapse before conditions develop to the point where an alarm sounds or where people begin to sense the cues of the fire itself. The fire cues that reach occupants can be the sight or smell of smoke, heat, the sight of flames, the sound of glass breaking, or the sound of an alarm signal from a smoke alarm, a heat detector, or a sprinkler system. The time to notification can be modeled, or it could be estimated if necessary using expert judgment.

Fire growth and smoke transport models can be used with detector/sprinkler activation models to estimate this period of time. Some models that can be used include ASET,[2] which estimates the temperature and position of the smoke layer in the room of fire origin; DETACT,[3] which models heat detection and sprinkler activation; or BREAK1,[4] which estimates time until glass breaks.*

Reaction Time

Reaction time is the time it takes an occupant to perceive the alarm or fire cue and decide to take action. For example, if a person is asleep when the smoke alarm sounds, it will take some period of time for the person to wake up, to identify the sound as the smoke alarm, and to decide to leave. There is currently no generally accepted modeling technique available for reaction time. The time used in an analysis may depend on observations (data) or expert judgment. An appropriate reaction time will depend on whether the person is awake or asleep, on his or her hearing ability, mental capacity, age (baby/child/adult), and so on.

Preevacuation Activity Time

Preevacuation activity time includes the time that elapses while the occupant is preparing to leave or seek refuge. Preevacuation activities involve all of the activities in which an occupant will engage from the time when he or she makes the decision to leave until the time he or she actually starts to travel toward an exit or an area of refuge. These activities may vary by occupancy. For example, hotel occupants might stop to pack their bags before they leave their rooms, whereas office workers may take time to shut off equipment and lock files. In an industrial setting, there may be a procedure that must be followed to safely shut down the plant's operations. To some degree, preevacuation activities can be reduced or eliminated through education or training. As with reaction time, there are no generally accepted modeling techniques available for preevacuation activity time, and the time used in an analysis may depend on observations (data) or expert judgment.

In reality, reaction time and preevacuation activity time are often considered together. In data collection exercises, it is generally not possible to separate the two time components, and the results will be reported as a single, combined time from notification to the time that movement toward the exit begins. Some of the data on preevacuation delays that has been obtained from postfire behavior studies and evacuation drills will be presented later in this chapter.

Travel Time

Travel time is the final component in the calculation of evacuation time. It is defined here as the time to move to a location of safety. There are various calculation or estimation techniques available for travel time. Some simple calculation methods can be found in FPEtool,[5] which is available from the National Institute for Standards and Technology (NIST) in the United States. These are based on some of the hand calculation methods described later in this chapter.

*The mention of these models does not represent or imply an endorsement of the models or the organizations that developed them.

ESTIMATING EVACUATION TIME

For evacuation modeling, several types of data are needed, either as model inputs or as considerations for the designer in setting up an analysis of a building design. A major data category that overarches the components of evacuation is occupant factors. Occupant factors include the characteristics of the people who would be expected to populate a building, whether on a permanent or transient basis. These factors include age, agility, commitment to the task at hand, familiarity with the building, level of training in what to do in emergencies, and many others.

More specifically, to calculate evacuation time, data is needed on delay times and travel times for a range of occupancy types. What types of delays should be expected, and how long they may last, is very often a function of the characteristics of the occupants. Likewise, travel times will be impacted by the characteristics of the occupants.

Factors Related to Delay Times

Delay times, also referred to as premovement time, initial response time, or time to start, can last from a few seconds to several minutes or more. It is important to remember that during this period of delay, people might be simply ignoring available cues, or they might be engaged in preevacuation activities as discussed earlier. As described previously, delay time includes time to notification, reaction time, and preevacuation activity time.

Several factors can result in variations in delay times. These factors, which are also related to the characteristics of the occupants, include

- Effectiveness of different cues
- Effectiveness or training
- Time of day, weather, and so on

Alarm devices use different sounds and, as a result, there can be confusion among building occupants as to what the sound is that they are hearing. And the alarm itself does not give people information as to what actions they should take. When building occupants hear an alarm, will they know if it is a burglar alarm or a fire alarm? Will they know if they should evacuate, or wait for further instructions? Voice communication systems, on the other hand, can convey information to building occupants and can decrease delay times by telling people what the situation is and what they are expected to do and how they should do it.

Training has been shown in studies to decrease delay times.[6] Trained building occupants can be expected to know where the closest exits are, should be able to recognize the alarm signal and know what to do, and could be expected to have shorter delay times. In buildings such as theaters and shopping centers, where the building occupants are not expected to be familiar with the alarms and exits, trained staff can reduce delay times significantly by directing occupants to the nearest exits immediately on hearing an evacuation signal.

Time of day and weather can have an impact on premovement delays. People may be reluctant to leave a building during a storm, in cold weather, or during the night. People may need extra time in winter to dress themselves and small children warmly.

Various characteristics of the occupants can also impact delay times. People with hearing impairments may not hear or interpret the sound of an alarm as quickly as people without impairments. People with mobility impairments may be slower to prepare themselves to evacuate or move to another location in the building. People who are engrossed in an activity may be too preoccupied to hear an alarm or warnings from other occupants, and then may be reluctant to leave what they are doing to take any protective actions.

Available Data on Delay Times

There are two principal sources of data on delay times: postfire survey questionnaires and videotaped observations from drills. Each method of data collection has its own advantages and disadvantages. Postfire survey questionnaires provide a method to collect information from real fires. However, it is very difficult for people to accurately estimate time lines for events in the past, particularly for traumatic events. Another problem is the subjectivity of the observations. For example, when people are asked to describe the thickness of smoke they traveled through or the duration of events, there is often a wide disparity in the descriptions among people who were in the same space at the same time. Videotaped observations allow the collection of very precise timelines, occupant densities, and travel flows in corridors and through doorways; however, the building occupants are not operating under any threat, and it is not clear to what degree observations from a fire drill will provide a good estimate of delay times or travel speeds in real fires. A third alternative method that has been mentioned recently is the use of video recordings from security cameras operating during a fire incident. Although the existence of such recordings has been mentioned, no data from the tapes has been reported yet in the literature.

Until behavioral models exist that can accurately predict the activities and behaviors of occupants before they begin to leave a building, it will be necessary for a designer evaluating an engineered design to provide an estimate of the duration of time those activities will require. Although a database of "accepted values" does not yet exist, there are summaries of delay times observed in several evacuation drills and actual fires available in the literature.[7]

One such summary report is based on five case studies that involved two sets of evacuation drills in apartment buildings, one set of office building drills, an actual apartment building fire and a fire in a megastructure complex.[8] The five case studies are part of an ongoing data collection project that is part of the development of the National Research Council of Canada's fire risk model. These studies uncovered a broad range in the delay times that can occur and provided an indication of some of the factors that can result in delays. The times observed in these studies cannot be taken at face value as the "correct" times a designer should use, but they do provide an indication of the range of times that exist in real-life situations.

The main factor influencing delay times in the evacuation drills was the audibility of the alarm system. The evacuation drills in apartment buildings took place during two research projects and involved seven mid- and high-rise buildings. In the two mid-rise apartment buildings where the performance of the alarm systems was described as "good," the average time for occupants to begin evacuation was 2.82 min. For the two mid-rise apartment buildings with alarm system performance described as "bad," the average delay time increased to 8.92 min.

Alarm system performance in two of the high-rise apartment buildings was described as "good," but the average delay time in those evacuations was quite different: 2.80 min in one and 5.32 min in the other. This discrepancy pointed out another factor that can significantly influence delay time—the weather. Since it was snowing at the time of one of the high-rise evacuation drills, the occupants took the time to dress warmly before leaving their apartments, adding approximately 2.50 min to the mean delay time. Overall in the apartment drills, the shortest average delay time for a building was 2.50 min and the longest was 9.70 min. Clearly, then, the delay time selected by a designer in the calculation of total evacuation time can greatly impact the final result and must be chosen with care.

The short delay times observed in the two office building evacuation drills demonstrated the combined effect of "good" alarms, training of occupants, and the use of fire wardens to assist in the evacuation. The delay times in the two drills averaged 0.60 min and 1.05 min.

The activities most frequently reported in postdrill questionnaires were gathering valuables, getting dressed, and notifying others. To these activities, the participants in the residential drills had added: looking in the corridor, finding children, finding pets, and moving to the balcony.

A building designer must be cautious when using delay time data from evacuation drills as input to an evacuation model, as drills might underestimate the amount of time an occupant will delay. Although one might expect that occupants will move more quickly in an actual fire, it often takes longer, while the occupants attempt to sort through ambiguous cues and determine whether or not they really need to act.[9]

The postfire human behavior study provided important evidence that evacuation might take longer in an actual fire than in a drill. The fire started on the fifth floor of a 30-story building at approximately 5:00 a.m. on a winter morning. Six building occupants died in two stairwells while attempting to evacuate. The building occupants who participated in this study filled out questionnaires 2 to 3 wk after the fire. Because of the time that elapsed between the fire and the survey, the occupants often rounded off the times they reported, but the study still provided important information on the range of time between various activities and events. Although the respondents in this study reported delays in beginning evacuation that ranged from 0 to

12 hr, close to half of the occupants attempted to leave within the first hour of becoming aware of the fire. And because no one above the fire floor who started evacuating after 5:30 a.m. was able to reach ground level on his or her own, the activities of the occupants in the first hour are of most interest. The average delay time for occupants who started to evacuate in the first hour was 10.50 min.

The human behavior study of the megastructure complex involved the explosion and fire that impacted the two 110-story World Trade Center towers in New York City in 1993. Building occupants had been trained, as had the occupants in the office drills mentioned previously, but in this case they were trained to wait on their respective floors for instructions. Since the emergency control center was destroyed in the explosion, the fire alarm system did not sound and no messages were transmitted. Occupants were forced to rely on ambiguous cues to alert them to the incident. Since the explosion was closer to the base on one tower, cues in that tower were somewhat less ambiguous than in the other. The delay times reported for the tower closer to the blast ranged from 0 to 4.08 hr, with a mean time of 11.03 min and a median time of 5.00 min. For the other tower, the delay times ranged from 0 to 3.08 hr, with a mean time of 25.40 min and a median time of 10.00 min.

Additional data need to be collected before a database exists that will provide precise estimates suitable for use, directly, in evacuation modeling. This set of studies illustrates, however, the variation that exists among different types of occupancies, between occupancies of the same type and between drills and actual incidents, as well as the role of alarm effectiveness, training, and weather.

It is important to mention that the delay times described here are mean times. The distribution of delay times shown in Figure 4.2.1 is typical, with most times relatively short, but with a long tail that can stretch to infinity (representing building occupants who never leave the building during the incident). The data in Figure 4.2.1 comes from a fire drill in a one-story department store.[6] A fire safety engineer or building designer must take into consideration the actual distribution of delay times in evaluating an engineered design.

As mentioned earlier, some of the data collected has been summarized in a recent paper that proposed a database of travel speed and delay time data.[7] The delay time data from that paper can be found in Table 4.2.1. The studies represented in this table involved hotels, office buildings, department stores, and a training facility. The user is cautioned to refer to the source documents for the full context of the experiments and incidents before applying the data to his or her application, otherwise, important differences between the evacuations that were the source of the data and the design being evaluated will be missed, and the resulting analysis could be completely invalid.

Factors Related to Travel Time

Travel time is a function of travel speed and distance to the exit and will vary among occupants. Evacuation models handle the calculation of travel time in various ways. Some evacuation models require the user to set a travel speed that will apply to all occupants throughout the evacuation, but this method does not take into account the effect of crowdedness, which will slow the travel speed of the occupants and increase their travel and total evacuation time. Another problem is that a uniform travel speed does not take into consideration the differing abilities of the building's occupants.

Travel time is to some degree a function of exit choice, because exit choice will determine travel distance. Buildings can be designed with multiple exits in the hope that people will use the closest exit in an emergency, and thereby reduce their evacuation

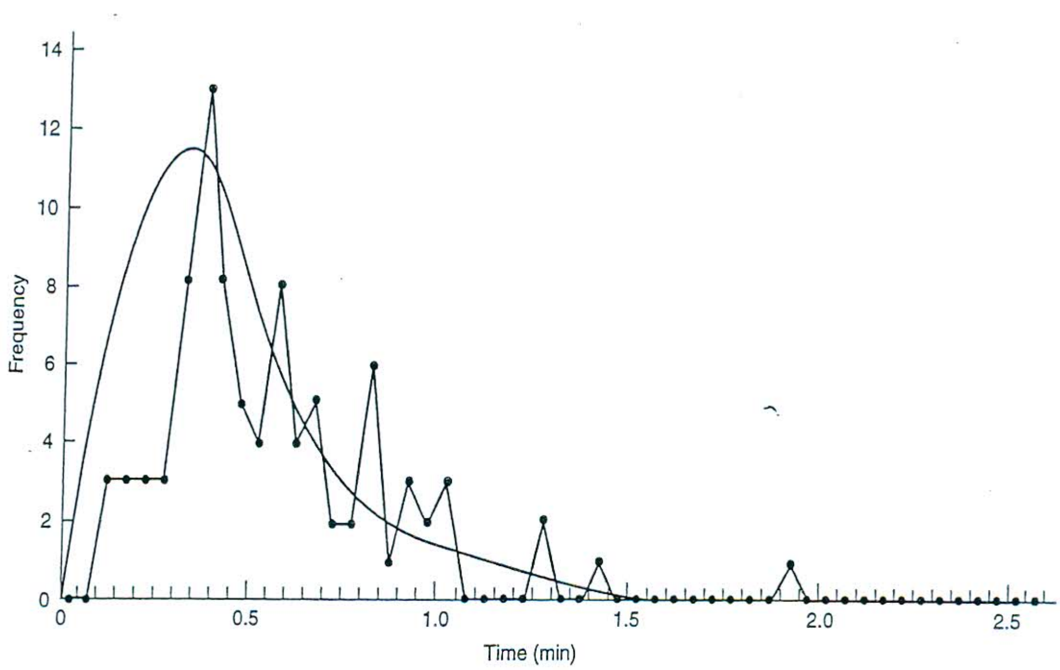

FIGURE 4.2.1 *Experimental and Theoretical Premovement Times in a Department Store Evacuation*

TABLE 4.2.1 *Delay Times (Minutes) Derived from Actual Fires and Evacuation Exercises Reported in the Referenced Literature*

Event Description	*N*	Min	1st Q	Median	3rd Q	Max	Mean	Factors
High-rise hotel[10]	536	0	3.3	60.0	130.9	290	n/a[a]	MGM Grand Hotel fire, no alarm notification, grouped data from questionnaires
High-rise hotel[11]	47	0	2.0	5.0	17.5	120	n/a	Westchase Hilton Hotel fire, no alarm in early stages, grouped data from questionnaires
High-rise office building[12]	85	0	2.0	5.0	10.0	245	11.3	World Trade Center explosion and fire, no alarm notification (building closer to explosion)
High-rise office building[12]	46	0	4.5	10.0	31.5	185	28.4	World Trade Center explosion and fire, no alarm notification (building further from blast)
High-rise office building[13]	107	1.0	1.0	1.0	1.0	~6.0	n/a	Fire incident, no alarms, data from interviews with occupants of four floors of building (11 interviewees were trapped)
High-rise office building[14]	12	0.5	n/a	1.0	n/a	2.3	1.2	Unannounced drill on three floors; data for first person to reach each of four stairwell doors to wait for voice instruction; trained staff; data from video recordings
Mid-rise office building[15]	92	0	0.4	0.6	0.8	<4	0.6	Unannounced drill, good alarm performance; fire wardens; warm day
Mid-rise office building[15]	161	0	0.5	0.9	1.4	<5	1.1	Unannounced drill, good alarm performance; fire wardens; cool day
One-story department store[16,17]	95	1	0.2	0.3	0.5	0.9	0.4	Unannounced drill; trained staff; data here derived from grouped data for 95 participants
Three-story department store[17]	122	0.05	n/a	n/a	n/a	1.6	0.6	Unannounced drill; trained staff; times distilled from analysis of videotapes
One-story department store[17]	122	0.07	n/a	n/a	n/a	1.7	0.5	Unannounced drill; trained staff; times distilled from analysis of videotapes
One-story department store[17]	71	0.03	n/a	n/a	n/a	1.0	0.4	Unannounced drill; trained staff; times distilled from analysis of videotapes
High-rise apartment building[18]	n/a	0	n/a	n/a	n/a	n/a	10.5	Forest Laneway fire; for occupants who attempted to evacuate in the first hour, based on questionnaire responses
	219	0	n/a	187.8	n/a	720	190.8	Forest Laneway fire, for all occupants
High-rise apartment building[19]	33	0.3	0.8	1.3	4.4	10.2	2.8	Unannounced drill; good alarm performance
High-rise apartment building[19]	93	0.4	1.5	3.6	6.9	18.6	5.3	Unannounced drill; good alarm performance; heavy snow during drill
High-rise apartment building[13]	27	1.0	2.0	8.0	14.0	>20	n/a	Fire incident in early morning, alarm functioned, fewer than half the occupants evacuated
Mid-rise apartment building[20]	42	0.6	1.0	1.4	3.0	>14	2.5	Unannounced drill; good alarm performance
Mid-rise apartment building[20]	55	>0.5	1.6	4.4	13.5	>21	8.4	Unannounced drill; poor alarm performance
Mid-rise apartment building[20]	77	>0.3	1.9	7.7	19.1	>24	9.7	Unannounced drill; poor alarm performance
Mid-rise apartment building[20]	80	>0.3	1.2	2.5	3.7	>12	3.1	Unannounced drill; good alarm performance
Training facility[21]	566	<0.2	0.7	1.1	1.5	>5	n/a	Testing sleeping subjects at a training facility

[a]n/a: not reported.

time. It has been shown time and again, however, that people tend to use the exit with which they are familiar, even if there is a closer emergency exit.[22] Without training, or instructions from trained staff, it may not be appropriate to assume that people will take the shortest route out of a building.

Other occupant characteristics impact both delays and travel time, but until very recently much of the necessary data to calculate their effects was not available. One important characteristic for which data has not been readily available is mobility, but a series of papers on the characterization of occupants of buildings, with particular emphasis on disabled occupants, was recently published. The series of papers covered the following:

- Prevalence, type, and mobility of disabled people
- Capability of disabled people to move horizontally or on an incline
- Capability of disabled people to negotiate doors
- Capability of disabled people to read and locate exit signs

The first paper documents a study that was done in Northern Ireland to estimate the number of disabled people who leave their homes and should be expected to use a variety of public buildings.[23] The study also looked at what percentage of the mobile population consists of the mobility-impaired as well as to what degree those who use public places are disabled, concentrating on disabilities that would influence a person's ability to escape a fire. According to this study, almost 8 percent of the total mobile population has a mobility impairment of some sort and 0.14 percent use a wheelchair. The study also looked at the use of public buildings by people with disabilities and found that approximately 40 percent of mobility-impaired adults frequent theaters and sports facilities, almost 60 percent stay in hotels, almost 30 percent are employed, and approximately 50 percent frequent eating and drinking establishments. The paper also presents detail on the frequency of use of public spaces and degree of mobility (whether or not they require assistance). A design team should be able to calculate, using the data presented in the paper, the proportion of building occupants likely to have a mobility impairment. Other types of disabilities that impact the ability to evacuate are also detailed, including dexterity, reaching and stretching, seeing, hearing, and mental abilities.

The second paper in the series provides important data on the travel speed of a mobility-impaired population on horizontal paths, ramps, and stairs, with and without assistance.[24] For those traveling without assistance on horizontal paths, the mean speed for the mobility-impaired group was 2.62 ft/s (0.80 m/s), compared to 4.10 ft/s (1.25 m/s) for those not mobility impaired. The mean travel speed for the mobility impaired varied by type of aid required, from 1.87 ft/s (0.57 m/s) for walker users to 3.12 ft/s (0.95 m/s) for those who did not use an aid. Electric wheelchair users had a mean travel speed of 2.92 ft/s (0.89 m/s) whereas manual-wheelchair users had a mean speed of 2.26 ft/s (0.69 m/s). Travel speed data is also presented in the paper for movement on ramps, up and down stairs and around corners. Information on the study participants' use of travel paths included observations on the amount of space used by people as they made their way along corridors or on stairs, the use of handrails, and difficulties negotiating stairway landings. An important added consideration covered in this paper is the rest time that many participants required while negotiating the 164-ft (50-m) paths, and the recovery time required by those who completed the 164 ft (50 m) distance without stopping.

The third paper in the series looks at the ability of disabled people to use doors.[25] The data in the paper include the percentage of mobility-impaired participants who could not negotiate doors with various closing forces and the time needed to negotiate doors of various closing forces, overall and by type of aid used. The authors conclude in this paper that the travel times predicted for disabled building occupants must include the time needed to negotiate doors.

The fourth and final paper in the series looks at the ability of disabled people to locate and read exit signs.[26] The study evaluated three types of exit signs—nonilluminated signs, internally illuminated signs, and light emitting diode (LED) signs. The paper presents data on the distances required by those with and without vision disabilities to locate and read exit signs and concludes that LED signs are the most visible and legible. The study did not, however, evaluate the ability of the participants to locate and read signs in the presence of distractions such as contrasting colors and smoke.

When an engineered design is being developed for public assembly properties, the design team must consider the characteristics of a population that accurately reflects the expected user population. This set of papers describes research on disabled groups in Northern Ireland. Whether or not it is reasonable to extrapolate the results to the rest of the world, this research provides data that begin to answer critical questions about the population at risk in public places.

Similar data must be collected for the full range of occupancy types. A great deal of data on travel speeds has been collected and reported in the literature for a long time. To put the reported data into the correct context, it is important to note the factors that can result in variations in movement speed. These include crowd density; the mobility, age and other characteristics of the occupants; the presence of family groups; the presence of smoke; and lighting and other design features. As the density of the crowd increases, the ease and speed of movement decreases until the crowd is moving at a shuffling pace. Family groups will attempt to stay together and will move at the speed of the slowest person. The presence of smoke can slow people down, or it can cause them to change directions or ultimately to stop their evacuation. Low lighting can slow people, particularly on stairs, and the evenness of the exit path and the roughness or smoothness of the walls along the exit path can also impact travel speeds.

Some of the data on travel speeds that has been collected has been summarized in a recent paper.[7] The data collected include the following types of occupancies: transport terminals, apartment buildings, assembly properties, industrial buildings, and hotels. Data for both able-bodied and mobility-impaired subjects are also available. The summary data from that paper are shown in Table 4.2.2. Again, the user is cautioned to refer to the source documents for the full context of the experiments and incidents before applying the data to his or her application.

TABLE 4.2.2 *Travel Speeds Reported in the Referenced Literature*

Type of Situation	Measured Travel Speeds				
A. Where Density Was Reportedly Not a Factor					
Transport terminals[27]	265 ft/min on walkways (1.35 m/s)				
Average under "normal conditions"[28]	60 m/min (1.0 m/s)				
Experiment with disabled subjects[29]					
	Min	1st Q	3rd Q	Max	Mean
On horizontal (m/s)					
All disabled subjects	0.10	0.71	1.28	1.77	1.00
With locomotion disability	0.10	0.57	1.02	1.68	0.80
No aid	0.24	0.70	1.02	1.68	0.95
Crutches	0.63	0.67	1.24	1.35	0.94
Cane	0.26	0.49	1.08	1.60	0.81
Walker/rollator	0.10	0.34	0.83	1.02	0.57
Without locomotion disability	0.82	1.05	1.34	1.77	1.25
Unassisted wheelchair	0.85	—	—	0.93	0.89
Assisted ambulant	0.21	0.58	0.92	1.40	0.78
Assisted wheelchair	0.84	1.02	1.59	1.98	1.30
On upward incline					
All disabled	0.21	0.42	0.74	1.32	0.62
With locomotion disability	0.21	0.42	0.72	1.08	0.59
No aid	0.30	0.48	0.87	1.08	0.68
Crutches	0.35	—	—	0.53	0.46
Cane	0.21	0.38	0.70	1.05	0.52
Walker/rollator	0.30	—	—	0.42	0.35
Without locomotion disability	0.70	—	—	1.32	1.01
Unassisted wheelchair	0.70	—	—	—	—
Assisted ambulant	0.23	0.42	0.70	0.72	0.53
Assisted wheelchair	0.53	0.70	1.05	1.05	0.89
On downward incline					
All disabled	0.10	0.42	0.70	1.83	0.60
With locomotion disability	0.10	0.42	0.70	1.22	0.58
No aid	0.28	0.45	0.94	1.22	0.68
Crutches	0.42	—	—	0.53	0.47
Cane	0.18	0.35	0.70	1.04	0.51
Walker/rollator	0.10	—	—	0.52	0.36
Without locomotion disability	0.70	—	—	1.83	1.26
Unassisted wheelchair	1.05	—	—	—	—
Assisted ambulant	0.42	0.52	0.86	1.05	0.69
Assisted wheelchair	0.70	0.96	1.05	1.05	0.96
Mid-rise apartment drill[20]	0.47 m/s on stairs (ranged from 0.34 to 1.08 m/s among various adult age groups; one visually impaired person traveled 0.31 m/s)				
Mid-rise apartment drill[20]	0.44 m/s on stairs (ranged from 0.32 to 0.56 m/s among various adult age groups)				
Mid-rise apartment drill[20]	0.41 m/s on stairs (ranged from 0.30 to 0.47 among various adult age groups)				
High-rise apartment drill[19]	1.05 m/s (ranged from 0.57 to 1.20 m/s among various adult age groups)				
High-rise apartment drill[19]	0.95 m/s (ranged from 0.56 to 1.12 m/s among various adult age groups)				
B. Where Density Was a Factor					
Public places[27]	100–250 ft/min on walkways (0.51–1.27 m/s) 70–150 ft/min on stairs (0.36–0.76 m/s)				
Public places[28]	17 m/min minimum on horizontal (0.28 m/s) 11–16 m/min downstairs (0.18–0.27 m/s)				
Theaters and educational[28]	15–20 m/min (0.25–0.33 m/s) max 2.33 m/s				
Industrial buildings[28]	25–30 m/min (0.42–0.56 m/s) max 2.33 m/s				
Transport terminals[28]	20–25 m/min (0.33–0.83 m/s) max 2.10 m/s				
Descending stairs[28]	20–25 m/min (0.33–0.42 m/s) max 1.28 m/s				

(continued)

TABLE 4.2.2 *Continued*

High-rise office building drill[14]	Mean Speed	Density
Stair with full lighting	0.61 m/s	1.30 persons/m^2
Stair with reduced lighting	0.70 m/s	1.25 persons/m^2
Stair with photoluminescent material (PLM) installation and reduced lighting	0.72 m/s	1.00 persons/m^2
Stair with PLM only	0.57 m/s	2.05 persons/m^2
Mid-rise office building drill[15]	0.78 m/s down stairs	
Mid-rise office building drill[15]	0.93 m/s down stairs	

Hotel exercise—along corridor (m/s)[30]

	Min	1st Q	Med	3rd Q	Max	Mean
Daytime scenario 1						
Able-bodied participants	0.6	1.1	1.3	1.8	4.0	1.5
Wheelchair users	0.2	—	—	—	1.2	0.8
Walking disabled	0.1	—	—	—	—	—
Daytime scenario 2						
Able-bodied participants	0.3	0.9	1.1	1.3	1.6	1.1
Wheelchair users	0.4	—	—	—	0.7	0.6
Walking disabled	0.7	—	—	—	—	—
Nighttime scenario						
Able-bodied participants	0.5	1.1	1.3	1.7	3.8	1.5
Wheelchair users	0.5	—	—	—	0.9	0.7
Walking disabled	2.4[a]	—	—	—	—	—

[a]This person traveled at this speed for a distance of 4.9 m.

CALCULATION METHODS FOR TRAVEL TIME

Calculating the travel time for an individual alone is a fairly straightforward exercise: travel time will be the product of travel distance and walking speed. Calculating the travel time for a crowd of occupants is more complex. There are three fundamental characteristics of crowd movement: density, speed, and flow. Density of a crowd is defined as the number of persons per unit area (e.g., 2.0 persons/m^2). Density can also be expressed as the area per person (e.g., 0.5 m^2/person). Speed is the time rate of motion of the occupants, usually expressed in meters per second. Flow is the rate at which people pass a particular point, such as a doorway per unit of time (e.g., 2.0 persons/s). Along with path width, the three characteristics of crowd movement are related as follows:

$$\text{flow} = \text{speed} \times \text{density} \times \text{width}$$

As mentioned in the previous section, speed is a function of density. The more people there are in a space, the slower they move, until eventually they reach the point where they are at a shuffling speed. Flow and density have a more complex relationship. At low densities, the rate of flow is small, as there are few people in the stream. Flow rates again are slow at high densities where there is little movement. Optimal flow is achieved at a density of approximately 2.0 persons/m^2. For details on the derivation of this value, the reader is referred to the *SFPE Handbook of Fire Protection Engineering.*[31]

There are several different approaches to calculating egress time. Flows through doors or corridors can be calculated. Walking speeds can be calculated or can be used as input to mode to calculate evacuation time. These methods can be simple enough to do by hand, or can be carried out by computer models that may incorporate other behavioral factors.

Empirically Based Evacuation Time Equations

Figure 4.2.2 presents a comparison of observed evacuation times for tall buildings with derived equations for the prediction of total evacuation time.[32–34] Pauls's data[34] is based on measurements obtained from 29 evacuation drills, primarily in office buildings ranging from 8 to 21 stories high. Pauls observed evacuation times varying from approximately 10 s/story fc buildings with small populations to approximately 20 s/story fc buildings with large populations. The evacuation equations indicated in Figure 4.2.2 were developed from these observe evacuation times. The first equation,

$$T = 0.70 + 0.0133p$$

is to be applied to predict evacuation times in buildings with larg populations exceeding 800 persons/m^2 of effective stair width. T is the minimum time (min) to complete an uncontrolled total evacuation by stairs and p is the actual evacuation population/m of effective stair width, measured immediately above the discharge level of the stair.

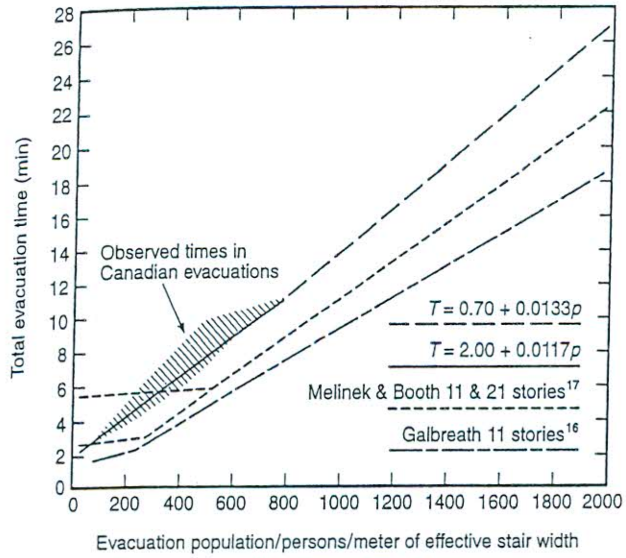

FIGURE 4.2.2 *Predicted and Observed Total Evacuation Times for Tall Office Buildings*

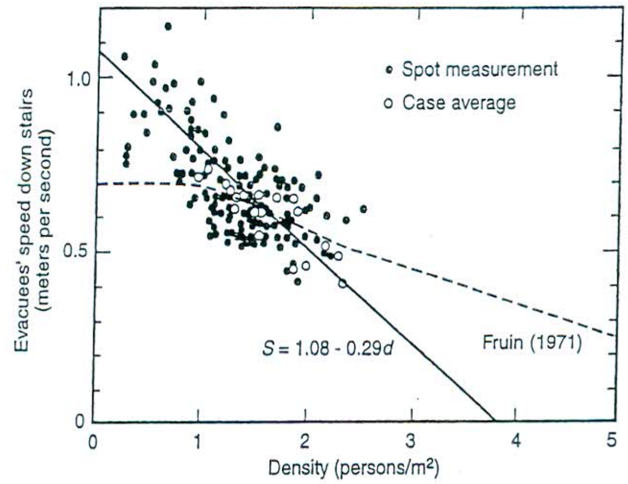

FIGURE 4.2.3 *Relation between Speed and Density on Stairs in Uncontrolled Total Evacuations*

It should be recognized that "effective stair width," as used by Pauls, is defined in the following manner.[34]

> This empirically based model describes flow as a linear function of a stair's effective width—the width remaining once the edge effects are deducted (150 mm or 6 inches from each wall boundary and 90 mm or 3.5 inches from each handrail centerline). It takes into account the propensity of people to sway laterally—especially when walking slowly in a crowd—and therefore to arrange themselves in a staggered traditional unit-width model based on presumed static dimensions of people's shoulders.

The second equation in Figure 4.2.2,

$$T = 2.00 + 0.0117p$$

is to be applied when the population/m of effective stair width is less than 800 persons.

Pauls[34] also examined the relationship between the speed of evacuation and the density on the stairs during the uncontrolled total evacuation, as indicated in Figure 4.2.3. It should be remembered that this movement would be in the vertical, downward direction.

Hydraulic Flow Calculations

The estimation of modeled evacuation time uses a series of expressions that relate data acquired from tests and observations to a hydraulic approximation of human flow.[35] Although the expressions indicate absolute relationships, there is considerable variability in the data. Figure 4.2.2 shows a typical relationship between the source data and the derived equation. The equations and relationships presented in the following paragraphs can be used independently or collectively to solve a complex egress problem. Such a coordinated collection of equations is demonstrated in the sample problem.

Effective Width, W_e. Persons moving through the exit routes of a building maintain a boundary layer clearance from walls and other stationary obstacles they pass. This clearance is needed to accommodate lateral body sway and assure balance.

Discussion of this crowd movement phenomena is found in the works of Pauls,[36] Fruin,[37] and Habicht and Braaksma.[38] The useful (effective) width of an exit path is the clear width of the path less the width of the boundary layers. Figures 4.2.4 and 4.2.5 depict effective width and boundary layer. Table 4.2.3 is a listing of boundary layer widths. The effective width of any portion of an exit route is the clear width of that portion of an exit route less the sum of the boundary layers.

Clear width is measured

1. From wall to wall in corridors or hallways
2. As the width of the treads in stairways
3. As the actual passage width of a door in its open position
4. As the space between the seats along the aisles of assembly arrangement
5. As the space between the most intruding portions of the seats (when unoccupied) in a row of seats in an assembly arrangement

The intrusion of handrails is considered by comparing the effective width without the handrails, and the effective width using a clear width from the edge of the handrail. The smaller of the two effective widths then applies. Using the values in Table 4.2.3, only handrails that protrude more than 2.5 in. (6 cm) need to be considered. Minor midbody height or lower intrusions such as panic hardware are treated in the same manner as handrails. Where an exit route becomes either wider or narrower, only that portion of the route has the appropriate greater or lesser clear width.

Density, *D*. Density is the measurement of the degree of crowding in an evacuation route and is usually expressed in persons/unit area. The calculations in this chapter are based on density expressed in persons/ft^2 (or persons/m^2).

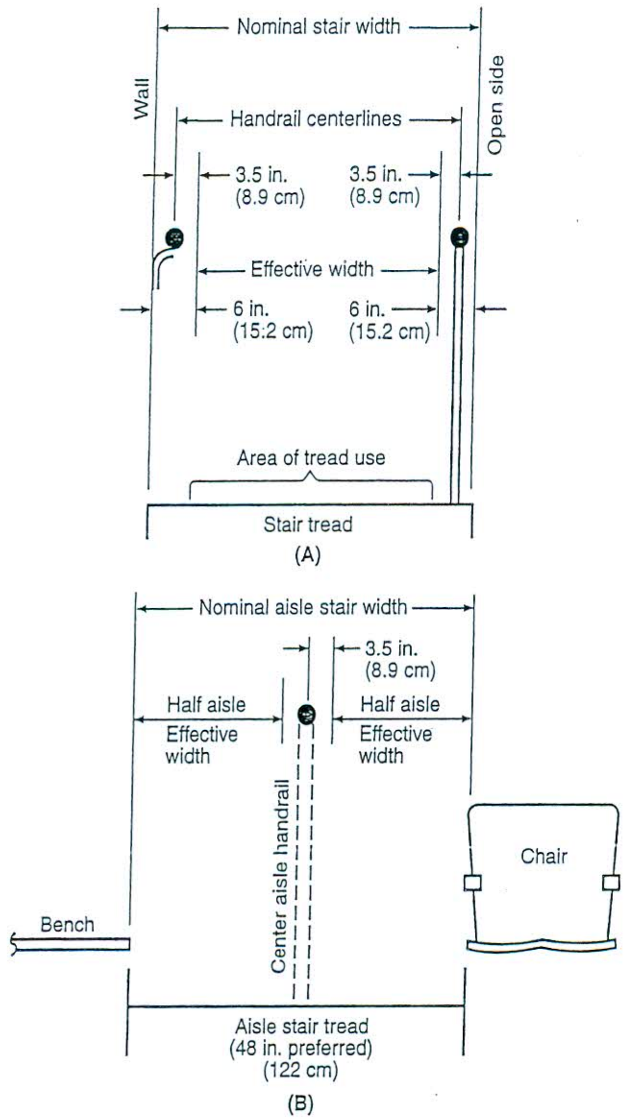

FIGURE 4.2.4 *Measurements of Effective Width of Stairs in Relation to Walls, Handrails, and Seating*

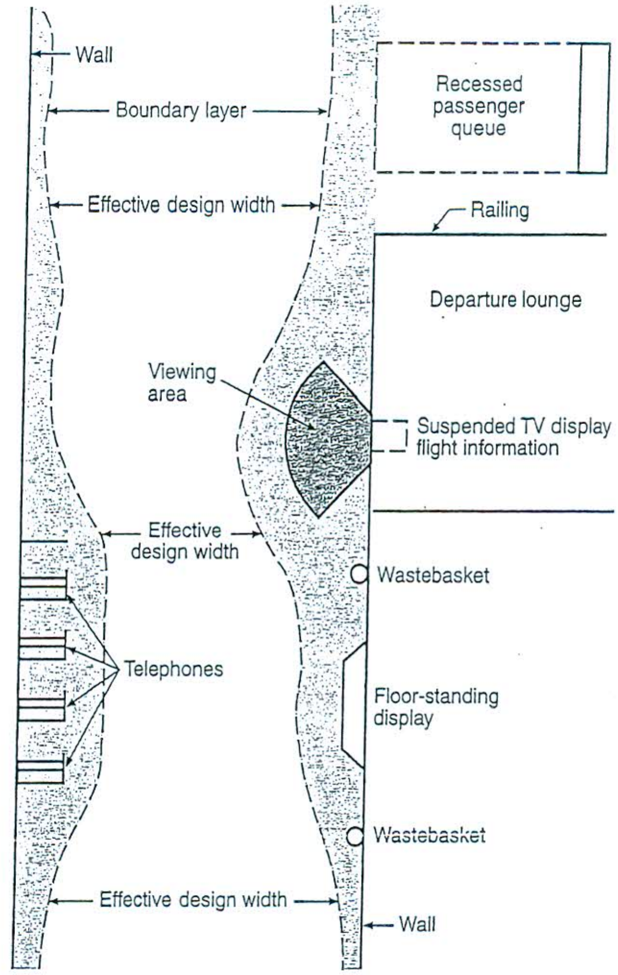

FIGURE 4.2.5 *Public Corridor Effective Width*

Unless information on the dispersion of occupants indicates otherwise, the density of the first exit element (aisle, corridor, ramp, etc.) is based on all of the served occupants. This will demonstrate the capacity limits of the route element and produce a value representing the maximum capacity of the element.

However, if the egressing population is widely dispersed, in terms of reaching the exit route element, the calculation is based on an appropriate time step. At each time increment, the density of the exit route is based on those who have entered the route minus those who have passed from it.

The density factors in subsequent portions of the egress system are determined by calculation. The calculation methods involved are contained in the section on transitions.

Speed of Exiting Individuals, *S*. The evacuation speed of a group is a function of the population density. The relationships presented in this section have been derived from Fruin,[37] Pauls,[36] and Predtechenskii and Milinskii.[39]

If the population density is less than about 0.05 persons/ft^2 (0.54 persons/m^2) of exit route (20 ft^2/person; 1.85 m^2/person), individuals will move at their own pace, independent of the speed of others. If the population density exceeds about 0.35 persons/ft^2 (3.8 persons/m^2), no movement will take place until enough of the crowd has passed from the crowded area to reduce the density.

Between the density limits of 0.05 and 0.35 persons/ft^2 (0.54 and 3.8 persons/m^2), the relationship between speed and density can be considered as a linear function. The equation of this function is

$$S = k - akD \tag{1}$$

TABLE 4.2.3 *Boundary Layer Widths*

Exit Route Element	Boundary Layer in.	Boundary Layer cm
Stairways—walls or side of tread	6	15
Railings, handrails[a]	3.5	9
Theater chairs, stadium benches	0	0
Corridor, ramp walls	8	20
Obstacles	4	10
Wide concourses, passageways	Up to 18	46
Door, archways	6	15

[a]Where handrails are present, use the value if it results in a lesser effective width.

where

S = speed along the line of travel

D = density (persons/unit area)

k = constant, as shown in Table 4.2.4, where
$k = k_1$ and $a = 2.86$ when calculating speed in feet per minute and density in persons per square foot
$k = k_2$ and $a = 0.266$ when calculating speed in meters per second and density in persons per square meter

Table 4.2.4 shows evacuation speed constant.

Figure 4.2.6 is a graphic representation of the relationship between speed and density. The speeds determined from Equation 2 are along the line of movement; for stairs this is along the line of the treads. Table 4.2.5 provides convenient multipliers for converting vertical rise of a stairway to a distance along the line of movement. The travel on landings must be added to the values derived from Table 4.2.5. The maximum speed occurs when the density is less than 0.05 persons/ft^2 (0.54 persons/m^2). These maximum speeds are listed in Table 4.2.6.

TABLE 4.2.4 *Constants for Equation 2, Evacuation Speed*

Exit Route Element		k_1	k_s
Corridor, Aisle, Ramp, Doorway		275	1.40
Stairs Riser (in.)	Tread (in.)		
7.5	10	196	1.00
7.0	11	212	1.08
6.5	12	229	1.16
6.5	13	242	1.23

Note: 1 in. = 25.4 mm.

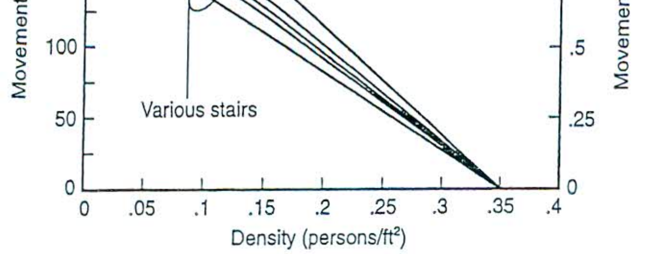

FIGURE 4.2.6 *Evacuation Speed as a Function of Density. $S = k - akD$, where D = density is persons/ft^2 and k is given in Table 4.2.4. Note that speed is along line of travel.*

TABLE 4.2.5 *Conversion Factors for Relating Line of Travel Distance to Vertical Travel for Various Stair Configurations*

Stairs Riser [in. (mm)]	Tread [in. (mm)]	Conversion Factor
7.5 (190)	10.0 (254)	1.66
7.0 (178)	11.0 (279)	1.85
6.5 (165)	12.0 (305)	2.08
6.5 (165)	13.0 (330)	2.22

Within the range listed in Tables 4.2.4 through 4.2.6, the evacuation speed on stairs varies approximately as the square root of the ratio of tread width to tread height. There is not sufficient data to appraise the likelihood that this relationship holds outside this range.

Specific Flow, F_s. Specific flow, F_s, is the flow of evacuating persons past a point in the exit route/unit of time/unit of effective width, W_e, of the route involved. Specific flow is expressed in persons/min/ft of effective width (if the value of $k = k_2$, from Table 4.2.4) or persons/s/m of effective width (if the value of $k = k_2$, from Table 4.2.4). The equation for specific flow is

$$F_s = SD \qquad (2)$$

where

F_s = specific flow

D = density

S = speed of movement

F_s is in persons/min/ft^2 when density is in persons/ft^2 and speed is in ft/min; F_s is in persons/s/m^2 when density is in persons/m^2 and speed is in m/s.

Combining Equations 1 and 2 produces

$$F_s = (1 - aD)kD \qquad (3)$$

where k is as listed in Table 4.2.4.

The relationship of specific flow to density is shown in Figure 4.2.7. In each case the maximum specific flow occurs when the density is 0.175 persons/ft^2 (1.9 persons/m^2) of exit route

TABLE 4.2.6 *Maximum (Unimpeded) Exit Flow Speeds*

Exit Route Element		Speed—Along Line of Travel ft/min	m/s
Corridor, Aisle, Ramp, Doorway		235	1.19
Stairs Riser [in. (mm)]	Tread [in. (mm)]		
7.5 (190)	10 (254)	167	0.85
7.0 (178)	11 (279)	187	0.95
6.5 (165)	12 (305)	196	1.00
6.5 (165)	13 (330)	207	1.05

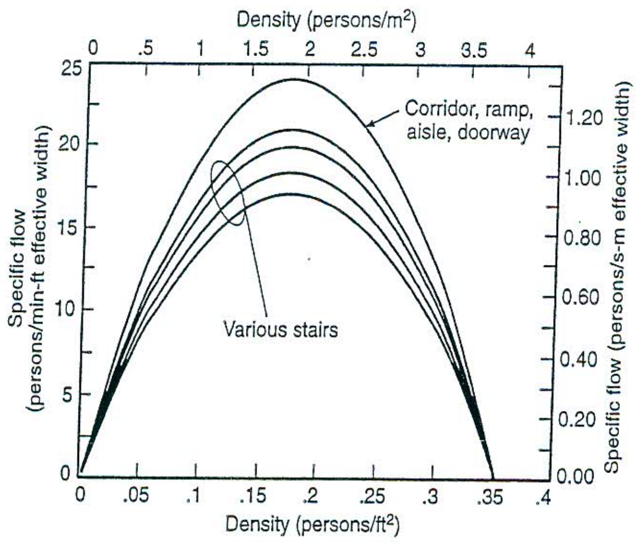

FIGURE 4.2.7 *Specific Flow as a Function of Density*

space. Maximum specific flows are associated with each type of exit route element; these are listed in Table 4.2.7.

Calculated Flow, F_c. The calculated flow, F_c, is the predicted flow rate of persons passing a particular point in an exit route.

The equation for actual flow is

$$F_c = F_s W_e \quad (4)$$

where

F_c = calculated flow
F_s = specific flow
W_e = effective width

Combining Equations 3 and 4 produces

$$F_c = (1 - aD)kDW_e \quad (5)$$

F_c is in persons/min when $k = k_1$ (from Table 4.2.4), D is in persons/sq ft^2, and W_e in ft.

F_c is in persons/s when $k = k_2$ (from Table 4.2.4), D is in persons/m^2, and W_e in m.

Time for Passage, T_p. Time for passage, T_p, that is, time for a group of persons to pass a point in an exit route, can be expressed as

$$T_p = P/F_c \quad (6)$$

where T_p is time for passage (T_p is in minutes where F_c is persons/min; T_p is in seconds where F_c is persons/s. P is population in persons.

Combining Equations 5 and 6 yields

$$T_p = P/(1 - aD)kDW_e \quad (7)$$

Transitions. Transitions are any point in the exit system where the character or dimension of a route changes or where routes merge. Typical examples of points of transition include the following:

1. *The point where two or more exit flows merge.* For example, the meeting of the flow from a cross aisle into a main aisle that serves other sources of exiting population. It also the point of entrance into a stairway serving othe floors (Figure 4.2.8).
2. *The point where a corridor enters a stairway.* There are ac tually two transitions: one occurs as the egress flow passes through the doorway; the other as the flow leaves the door way and proceeds onto the stairs.
3. *Any point where an exit route becomes wider or narrower.* For example, a corridor may be narrowed for a short distance by an intruding service counter or similar elemen The calculated density, D, and specific flow, F_s, differ before reaching, while passing, and after passing the intrusion (Figure 4.2.9).

TABLE 4.2.7 *Maximum Specific Flow, F_{sm}*

Exit Route Element [in. (mm)]		Maximum Specific Flow Persons/min/ft of Effective Width	Persons/s/m of Effective Width
7.5 (190)	10 (254)	17.1	0.94
7.0 (178)	11 (279)	18.5	1.01
6.5 (165)	12 (305)	20.0	1.09
6.5 (165)	13 (330)	21.2	1.16

The following rules apply to determining the densities and flow rates following the passage of a transition point:

1. The flow after a transition point is a function, within limits of the flow(s) entering the transition point.
2. The calculated flow, F_c, following a transition point cannot exceed the maximum specific flow, F_{sm}, for the route element involved multiplied by the effective width, W_e, of that element.

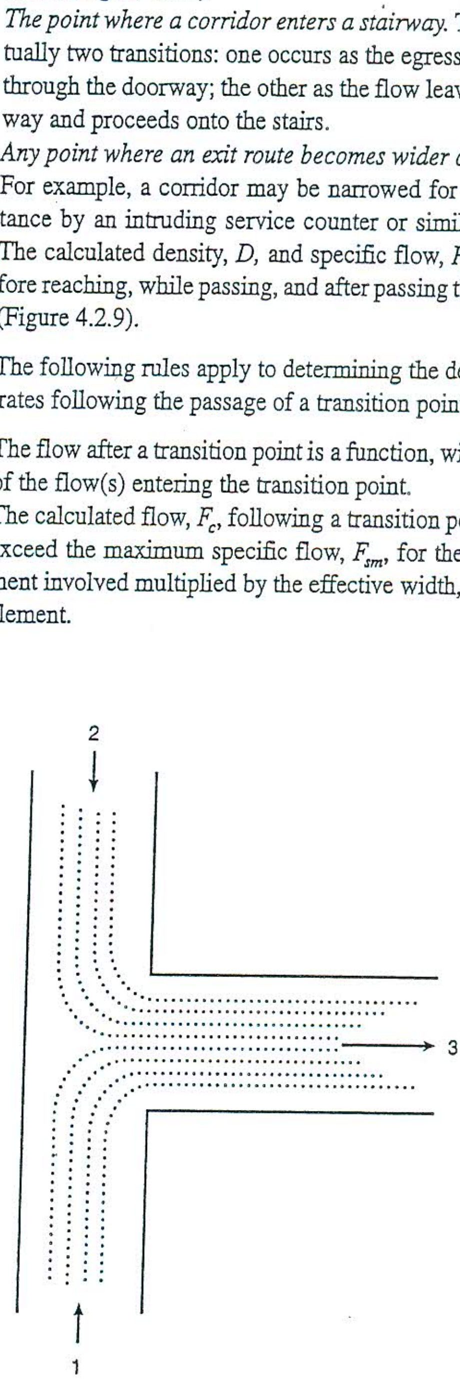

FIGURE 4.2.8 *Merging Egress Flows*

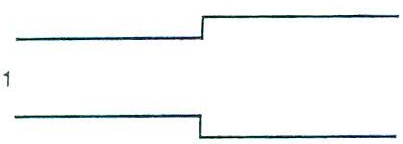

FIGURE 4.2.9 *Transition in Egress Component*

3. Within the limits of rule 2, the specific flow, F_s, of the route departing from a transition point is determined by the following equations:
   (a) For cases involving one flow into and one flow out of a transition point:

$$F_{s(\text{out})} = F_{s(\text{in})} W_{e(\text{in})} / W_{e(\text{out})} \tag{8a}$$

   where

   $F_{s(\text{out})}$ = specific flow departing from a transition point

   $F_{s(\text{in})}$ = specific flow arriving at a transition point

   $W_{e(\text{in})}$ = effective width prior to a transition point

   $W_{e(\text{out})}$ = effective width after passing a transition point

   (b) For cases involving two incoming flows and one outflow from a transition point, such as that which occurs with the merger of a flow down a stair and the entering flow at a floor:

$$F_{s(\text{out})} = \{\lfloor F_{s(\text{in})\text{-}1} W_{e(\text{in})\text{-}1} \rfloor + \lfloor F_{s(\text{in})\text{-}1} W_{e(\text{in})\text{-}2} \rfloor\} / W_{e(\text{out})} \tag{8b}$$

   where the subscripts (in-1) and (in-2) indicate the values for the two incoming flows.

   (c) For cases involving other merger geometries, the following general relationship applies:

$$\lfloor F_{s(\text{in-1})} W_{e(\text{in-1})} \rfloor + \cdots + \lfloor F_{s(\text{in-}n)} W_{e(\text{in-}n)} \rfloor = \lfloor F_{s(\text{out-1})} W_{e(\text{out-1})} \rfloor + \cdots + \lfloor F_{s(\text{out-}n)} W_{e(\text{out-}n)} \rfloor \tag{8c}$$

   where the letter n in the subscripts (in-n) and (out-n) is a number equal to the total number of routes entering (in-n) or leaving (out-n) the transition point.

4. Where the calculated specific flow, F_s, for the route(s) leaving a transition point, as derived from the equations in rule 3, exceeds the maximum specific flow, F_{sm}, a queue will form at the incoming side of the transition point. The number of persons in the queue will grow at a rate equal to the calculated flow, F_c, in the arriving route minus the calculated flow leaving the route through the transition point.
5. Where the calculated outgoing specific flow, $F_{s(\text{out})}$, is less than the maximum specific flow, F_{sm}, for that route(s), there is no way to predetermine how the incoming routes will merge. The routes may share access through the transition point equally, or there may be total dominance of one route over the other. For conservative calculations, assume that the route of interest is dominated by the other route(s). If all routes are of concern, it is necessary to conduct a series of calculations to establish the bounds on each route under each condition of dominance.

EXAMPLE: This example uses stairs of U.S. conventional size and is therefore presented in English units. Consider an office building (Figure 4.2.10) with the following features:

1. There are nine floors, 300 ft × 80 ft.
2. Floor-to-floor height is 12 ft.
3. There are two stairways, located at ends of building (no dead ends).
4. Each stair is 44 in. wide (tread width) with handrails protruding 2.5 in.
5. Stair risers are 7 in. wide; treads are 11 in. high.
6. There are two 4 ft × 8 ft landings per floor of stairway travel.
7. There is one 36 in. clear width door at each stairway entrance and exit.
8. The first floor does not exit through stairways.
9. Each floor has a single 8-ft wide corridor extending the full length of each floor. Corridors terminate at stairway entrance doors.
10. There is a population of 300 persons/floor.

SOLUTION A—FIRST ORDER APPROXIMATION

1. *Assumptions.* The prime controlling factor will be either the stairways or the door discharging from them. Queuing will occur; therefore, the specific flow, F_s, will be the maximum specific flow, F_{sm}. All occupants start egress at the same

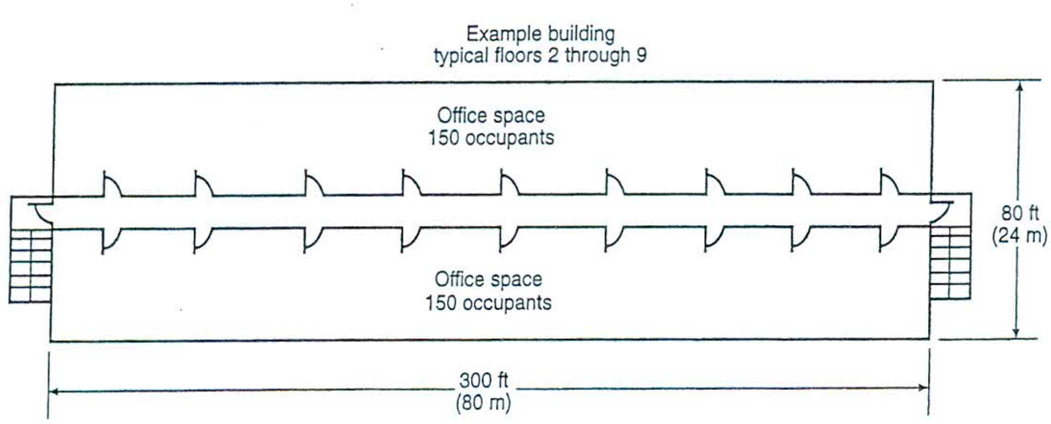

FIGURE 4.2.10 *Floor Plan for Example*

time. The population will use all facilities in the optimum balance.

2. *Estimate flow capability of a stairway.* From Table 4.2.3, the effective width, W_e, of each stairway is 44 − 12 = 32 in. (2.66 ft). Also, the effective width, W_e, of each door is 36 − 12 = 24 in. (2 ft). The maximum specific flow, F_{sm}, for the stairway (from Table 4.2.7) is 18.5 persons/min/ft effective width. Specific flow, F_s, equals maximum specific flow, F_{sm}. Therefore, using Equation 4, the flow from each stairway is limited to 18.5 × 2.66 = 49.2 persons/min.
3. *Estimate flow capacity through a door.* Again from Table 4.2.7, the maximum specific flow through any 36-in. door is 24 persons/min/ft effective width. Therefore, using Equation 4, the flow through any door is limited to 24 × 2 = 48 persons/min. Since the flow capacity of the doors is less than the flow capacity of the stairway served, the flow is controlled by the stairway exit doors (48 persons/stairway exit door/min).
4. *Estimate the speed of movement for estimated stairway flow.* From Equation 1, the speed of movement down the stairs is 212 − (2.86 × 212 × 0.175) = 105 ft/min. The travel distance between floors (using the conversion factor from Table 4.2.5) is 12 × 1.85 = 22.2 ft on the stair slope plus 8 ft travel on each of the two landings, for a total floor-to-floor travel distance of 22.2 + (2 × 8) = 38.2 ft. The travel time for a person moving with the flow is 38.2/105 = 0.36 min/floor.
5. *Estimate building evacuation time.* If all of the occupants in the building start evacuation at the same time, each stairway can discharge 48 persons/min. The population of 2400 persons above the first floor will require approximately 25 min to pass through the exit. An additional 0.36 min travel time is required for the movement from the second floor to the exit. The total minimum evacuation time for the 2400 persons located on floors 2 through 9 is estimated at 25.4 min.

SOLUTION B—MORE DETAILED ANALYSIS

1. *Assumptions.* The population will use all exit facilities in the optimum balance; all occupants start egress at the same time.
2. *Estimate flow density, D, speed, S, specific flow, F_s, effective width, W_e, and initial calculated flow, F_c, typical for each floor.* Divide each floor in half to produce two exit calculation zones, each 150 ft long. Determine the density, D, and speed, S, if all occupants try to move through the corridor at the same time; that is, 150 persons moving through 150 ft of an 8-ft wide corridor.

$$\text{Density, } D = 150 \text{ persons}/1200 \text{ ft}^2 \text{ corridor area}$$
$$= 0.125 \text{ persons/ft}^2.$$

From Equation 1, speed, $S = k - akD$.
From Table 4.2.4, $k = 275$.

$$S = 275 - (2.86 \times 275 \times 0.125) = 177 \text{ ft/min}.$$

From Equation 3, specific flow, $F_s = (1 - aD)kD$.

$$F_s = [1 - (2.86 \times 0.125)] \times 275 \times 0.125$$
$$= 22 \text{ persons/ft effective width/min}.$$

From Table 4.2.7, the specific flow, F_s, is less than the maximum specific flow, F_{sm1}; therefore, F_s is used for the calculation of calculated flow.

From Table 4.2.3, the effective width of the corridor is 8 − (2 × 0.5) = 7 ft.

From Equation 5, calculated flow, $F_c = (1 - aD)kD$

$$F_c = [1 - (2.86 \times 0.125)] \times 275 \times 0.125 \times 7$$
$$= 154 \text{ persons/min}.$$

Note: At this stage in the calculation, calculated flow, F_c, is termed "initial calculated flow" for the exit route element (i.e., corridors) being evaluated. This is because the calculated flow rate can be sustained only if the discharge (transition point) from the route can also accommodate the indicated flow rate.

3. *Estimate impact of stairway entry doors on exit flow.* Each door has a 36-in. clear width. From Table 4.2.3, effective width, W_e, is 30 − 12 = 24 in. (2 ft).

   From Table 4.2.7, the maximum specific flow, F_{sm}, is 24 persons/min/ft effective width.

   From Equation 8,

$$F_{s(door)} = [F_{s(corridor)} W_{e(corridor)}]/W_{e(door)} F_{s(door)}$$
$$= (22 \times 7)/2$$
$$= 77 \text{ persons/min/ft effective width}.$$

Since F_{sm} is less than the calculated F_s, the value of F_{sm} is used. Therefore, the effective value for specific flow is 24.

From Equation 4 the initial calculated flow, $F_c = F_s W_e = 24 \times 2 = 48$ persons/min through a 36-in. door.

Since F_c for the corridor is 154 whereas F_c for the single exit door is 48, queuing is expected. The calculated rate of queue buildup will be 154 − 48 = 106 persons/min.

4. *Estimate impact of stairway on exit flow.* From Table 4.2.3, effective width, W_e, of the stairway is 44 − 12 = 32 in. (2.66 ft).

   From Table 4.2.7, the maximum specific flow, F_{sm}, is 18.5 persons/ft effective width.

   From Equation 8, the specific flow for the stairway, $F_{s(stairway)}$, is 24 × 2/2.66 = 18.0 persons/ft effective width. In this case, F_s is less than F_{sm}, and F_s is used.

   The value of 18.0 for F_s applies until the flow down the stairway merges with the flow entering from another floor.

   Using Figure 4.2.6 or Equation 3 and Table 4.2.4, the density of the initial stairway flow is approximately 0.146 persons/ft² of stairway exit route.

   From Equation 1, the speed of movement during the initial stairway travel is 212 × (2.86 × 212 × 0.146) = 123 ft/min.

   From Solution A, the floor-to-floor travel distance is 38.2 ft. The time required for the flow to travel one floor level is 38.2/123 = 0.31 min (19 s).

   Using Equation 4, the calculated flow, F_c, is 18.0 × 2.66 = 48 persons/min.

   After 0.31 min, 48 × 0.31 = 15 persons will be in the stairway from each floor feeding to it. If floors 2 through 9 exit all at once, there will be 15 × 8 = 120 persons in the stairway. After this time, the merging of flows between the flow in the stairway and the incoming flows at stairway entrances will control the rate of movement.

5. *Estimate impact of merger of stairway flow and stairway entry flow on exit flow.* From Equation 9, $F_{s(\text{out-stairway})} = \{[F_{s(\text{door})} \times W_{e(\text{door})}] + [F_{s(\text{in-stairway})} \times W_{e(\text{in-stairway})}]\}/W_{e(\text{out-stairway})} = [(24 \times 2) + (18 \times 2.66)]/66 = 36$ persons/ft effective width.

   From Table 4.2.7, F_{sm} for the stairway is 18.5 persons/min/ft effective width. Since F_{sm} is less than the calculated F_s, the value of F_{sm} is used.

6. *Track egress flow.* Assume all persons start to evacuate at time zero. Initial flow speed is 177 ft/min. Assume that congested flow will reach the stairway in 30 s. At 30 s, flow starts through stairway doors. F_c through doors is 48 persons/min for the next 19 s. At 49 s, 120 persons are in each stairway, and 135 are waiting in a queue at each stairway entrance door.

   Note: Progress from this point on depends on which floors take dominance in entering the stairways. Any sequence of entry may occur. To set a boundary, this example estimates the result of a situation where dominance proceeds from the highest to the lowest floor.

   The remaining 135 persons waiting at each stairway entrance on the 9th floor enter through the door at the rate of 48 persons/min. The rate of flow through the stair is regulated by the 48 persons/min rate of flow of the discharge exit doors. The descent rate of the flow is 19 s/floor.

   Thus,

at 218 s (3.6 min)	All persons have evacuated the 9th floor.
at 237 s (4.0 min)	The end of the flow reaches the 8th floor.
at 401 s (6.7 min)	All persons have evacuated the 8th floor.
at 420 s (7.0 min)	The end of the flow reaches the 7th floor.
at 584 s (9.7 min)	All persons have evacuated the 7th floor.
at 603 s (10.1 min)	The end of the flow reaches the 6th floor.
at 767 s (12.8 min)	All persons have evacuated the 6th floor.
at 786 s (13.1 min)	The end of the flow reaches the 5th floor.
at 950 s (15.8 min)	All persons have evacuated the 5th floor.
at 969 s (16.2 min)	The end of the flow reaches the 4th floor.
at 1133 s (18.9 min)	All persons have evacuated the 4th floor.
at 1152 s (19.2 min)	The end of the flow reaches the 3rd floor.
at 1316 s (21.9 min)	All persons have evacuated the 3rd floor.
at 1335 s (22.3 min)	The end of the flow reaches the 2nd floor.
at 1499 s (25.0 min)	All persons have evacuated the 2nd floor.
at 1518 s (25.3 min)	All persons have evacuated the building.

COMPUTER SIMULATION AND MODELING OF EGRESS DESIGN

Simulation modeling may be appropriate for problems that would otherwise require costly, time-consuming, and tedious manual effort; those that cannot be solved through experimentation because of high costs or unacceptable risks to human participants; and for which past experience, intuition, or available data do not provide the proper insight.[40]

Types of Evacuation Models

Three types of evacuation models are currently available:

- Single-parameter estimation models
- Movement models
- Behavioral simulation models

Single-Parameter Estimation Models. Single-parameter estimation models are generally used for simple estimates of movement times. They can be hand calculations or simple computer models (e.g., flow times based on widths of exit paths or travel times based on distances).

Movement Models. Movement models generally handle large numbers of people in a network flow. This type of model treats occupants like water in a pipe or ball bearings in a chute. They tend to optimize occupant behavior, with all occupants moving at the same speed, with perfect knowledge of the building's layout and exit routes. Such models can be useful in benchmarking designs; if the calculated exit times using this type of model are insufficient for safe evacuation, then the actual evacuation time in a real fire will certainly be insufficient.

Behavioral Simulation Models. Behavioral simulation models consider more of the variables related to occupant movement and behavior. They treat occupants as individuals with unique characteristics. Occupants can move at different speeds, in reaction to the conditions in their surroundings. Because they are tracked individually, their exposure and reaction to toxic conditions while evacuating can be estimated by some of these models or by tenability or toxicity models that analyzed the simulation results. This type of model allows a more realistic simulation, but there are concerns with their use related to the lack of available data that would allow the prediction of human behavior in fire. In choosing a model, the user has to understand the underlying assumptions and be sure that those assumptions are appropriate to the analysis at hand.

Computer simulation and modeling have become important tools in designing adequate means of egress under a variety of occupancy and structural conditions. Evacuation modeling has become particularly important in recent years since standards-making organizations around the world have developed performance-based options for fire protection design. An essential element in the evaluation of an engineered design is a comparison of the results of the modeling of a range of fire scenarios, and the subsequent fire effects that can be expected, with the results of an evacuation model that will predict where and for how long people will be dispersed throughout a structure.

History of Evacuation Modeling

Evacuation modeling has a long history. In one study of the critical variables for fire safety in relation to buildings used to house the elderly, the problem of fire development and evacuation as a time-structured problem was considered.[41] This study analyzed the variables related to the occurrence and spread of fire relative to the population's ability to reach an area of refuge from the effects of the fire. The study established the variables for the fire on a continuum of a "critical time" and the parameters for the survival of the occupants on a continuum of a "reaction time."

The definition adopted for critical time is the time elapsed from the start of the fire to the attainment of intolerable levels. The definition for reaction time is reported as the amount of time used by the occupant to react to the fire and to achieve safety by evacuating the fire area or by obtaining a place of refuge from the effects of the fire. Thus, within the framework of these definitions, both the parameters of the problem of the human behavior factors involved in a fire in a building and the variables of the problem are considered. This conceptualization of a critical time for fire development within a building and of the reaction time required for occupants to perceive and respond to the fire threat, either by evacuation or movement to an area of refuge, has been studied thoroughly. It resulted in multiple computer models of this essential egress behavior since Caravaty and Haviland's study in 1967.[41]

A computer model that simulated the movement of people during evacuation through the floor of fire origin was developed in the mid-1970s.[42] This Markov-based model focused on the movement of people through a fire floor from the time of alarm until their safe exit or until they became casualties of the fire. Six variables affecting their movement were identified:

1. Objective location of the threatening stimuli in time and space
2. Occupants' prior knowledge of effective egress routes
3. Occupants' perception of the location and severity of the threat
4. Occupants' perception of available alternatives
5. Occupants' threat-reducing experiences prior to the current movement decision
6. The interjection of sudden interpretations to the occupants' goal-directed behavior

A modeling technique was developed in the early 1980s that appeared to have potential for comparing the evacuation behavior of occupants assisted by trained personnel with evacuation without assistance.[43] This model determined the escape potential from an area of a building based on a deterministic approach with a computer algorithm, and it evaluated the effects of fire growth and smoke movement on occupants as they try to egress. Occupant evacuation was simulated with evaluation of the effects of the egress design, the density of the occupants in the means of egress, the congestion at door or other restrictions, and the effects of the combustion products on occupants.

The concepts of critical time and reaction time as originally formulated by Caravaty and Haviland[41] were adapted into a determination of the available safe egress time (ASET) model. This model is a mathematical procedure for simulating of the conditions that develop between the time of fire ignition and the onset of untenable conditions for human occupancy. It was developed to evaluate the evacuation plans and procedures within a specific building.[2] This model required input data on the physical dimensions of the building areas, the means of egress, and the specified evacuation routes with the number and location of the occupants. The model provided an estimated average evacuation time and an estimated total evacuation time.

Building network evacuation models similar to the model of O'Leary and Gratz[44] were developed that evaluate the egress environment within the building and the characteristics of the population relative to density and location.[45] The models predicted evacuation flows and times, and identified queueing problems. The model was validated with evacuation data from high-rise federal office buildings and college dormitories.

An analytical queueing network model (QNM) was also developed to be used in the analysis of a building design relative to the suitability of the egress system.[46] This model provided estimates of the evacuation times, the average queue lengths along egress routes, potential impairments, and total egress probability.

The improvement and use of computer models for evacuation analysis in the late 1980s was examined and reviewed by Watts.[47]

During the 1990s, development of evacuation models accelerated. Fahy[48] developed a FORTRAN model called EXIT89 to predict evacuation times for high-rise buildings. This evacuation model was designed to work with two of the subprograms of HAZARD I,[49] FAST, and TENAB to estimate the hazard to the occupants from the modeled fire incident. It calculates the occupants' movement along the shortest evacuation routes or user-defined "familiar" routes, and the queuing of the occupants along these routes. The walking speeds in this model are derived from the occupant densities values developed by Predtechenskii and Milinskii.[39] The model has been further developed over the following decade to incorporate a range of real-life features, such as the presence of disabled occupants, premovement delays, choices in exit route selection, and so on.[50]

In recent years, improvements in computer technology have allowed a new generation of computer models that take advantage of the power of computers today and the sophistication of newer software tools. Many of these models are analogous to the CFD models of fire development. Rather than using network-node descriptions of a building, these models describe the building space as a mesh, or grid, and use complex spatial analysis and computer-generated route finding techniques. Rather than jump from node to node, as simulated occupants will appear to do in a network model, occupants will move from "tile" to "tile" in the grid that overlays the floor plan. This allows a more precise location of occupants throughout spaces.

The current generation of model all include the phenomena that EXIT89 sought to address. Some of the new models also include additional phenomena, but there are always tradeoffs between the completeness and detail of the models and the implied magnitude of data requirements. It is not clear that the net predictive power or accuracy is improved if simplified representations requiring limited data with moderate uncertainty are replaced by elaborate, highly sophisticated representations requiring enormous databases with large associated uncertainty and a heavy reliance on subjective estimation to compensate for a lack of field data. In short, the range of choices has expanded greatly over the past several years, but the value of more simple models has not been diminished.

Due to the variation in techniques used for modeling evacuation, it is not possible to present the equations used. For that level of detail, the reader is referred to the documentation for the particular model of interest. And, as the available list of evacuation models grows, it would not be feasible to list the models here. No truly objective comparison has been undertaken of the range of evacuation models currently available, but a brief overview of many of the currently available programs can be found in the literature.[51–53] The degree to which behavior is simulated varies extensively among available models. Care must be taken in choosing a model. The complexity of some models implies a greater predictive capability, but the scarcity of data available on behavior means that a great number of assumptions are imbedded in the models, and the appropriateness of those assumptions is critical in evaluating the validity of a model's results.

Chapter 3–14 of the *SFPE Handbook of Fire Protection Engineering,* "Emergency Movement," includes guidance on the selection of evacuation models. A list of questions the user should be able to answer about the model selected for analysis is provided.

SUMMARY

It is critically important in estimating the time to evacuate a building that attention be paid to more than the travel time necessary to clear spaces. The total time to evacuate a building, or to bring occupants to a location of safety, must include delay times before movement or refuge actions begin. Whether the calculations are based on data or on calculations, and regardless of whether the calculations are done by hand or by computer, a valid time estimate cannot be made without consideration of time to start. The characteristics of the building occupants and of the building itself will govern the choice of appropriate delay time estimates, as well as the calculation of travel times.

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