SUGGESTIONS ON EVACUATION MODELS AND RESEARCH QUESTIONS

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INTRODUCTION

Most of this paper is based on an earlier paper given as a keynote presentation at Pedestrian and Evacuation Dynamics 2003, held at the University of Greenwich and published in *Proceedings of the 2nd International Conference*.[1] Thus it is appropriate to ask why the author was asked to address the same topic at the Third International Symposium on Human Behaviour in Fire being held a year later.

One reason is that some people who are involved with modeling evacuation aspects of human behaviour did not participate in the Pedestrian and Evacuation Dynamics Conference (also known as PED 2003). Another is that many people normally participating in the International Symposia were not at the Pedestrian and Evacuation Dynamics Conference. The third reason is that the most obvious deficiencies in pedestrian and evacuation dynamics modeling have been addressed, and could be even better addressed, by those focused on human behaviour research. The most obvious deficiencies—at least as perceived by this author (but shared by others at the PED Conference)—were failures of many of the models to adequately represent actual crowd and evacuation behaviour. This was sometimes coupled with flawed use of the models. These are, respectively, problems of design and usage. For example, some models may have seductively attractive graphic output which, while visually appealing, masks underlying weaknesses in the model or the input assumptions.

The bottom line, at least in the view of this author, is the need to put even more effort into documenting what actually happens in the real world—which is much richer and more complex than models can now depict.

Within the Third International Symposium on Human Behaviour in Fire are addressed a number of real-world issues, ranging from problems with the collection, dissemination,, interpretation and use of human behaviour data through to how societal interventions such as codes and standards are developed, adopted and enforced. The challenges associated with such problems and interventions are so important that they should be discussed much more than has been the case to date. Thus the goal of this paper is to help provoke discussion, especially at a time that highly visible, “big-ticket” research is being conducted by various established and new-to-the-field researchers and organizations, most prominently in relation to the World Trade Center (WTC) disaster on September 11, 2001. Moreover, as discussed in a separate paper at this Symposium (by Pauls and Wearne), disasters such as the WTC and the Station Night Club fire in Rhode Island have been subjected to important, detailed examination by journalists as well as by conventional researchers.

These disasters and the varied research responses, plus public policy developments, are influencing the future of fire safety in ways that are still unclear as we again gather to discuss human behaviour in fire at the International Symposium and contribute more first drafts of history.

RECENT EFFORTS TO COLLECT OR ORGANIZE DATA FOR EVACUATION MODELING

This brief review addresses only the proceedings of the most recent, prior International Symposium on Human Behaviour in Fire (2001) and International Conference on Pedestrian and Evacuation Dynamics (2003).[2,3] Especially notable in the former is the effort by Fahy and Proulx “Toward creating a data base on delay times to start evacuation and walking speeds for use in evacuation modeling.'[4] Complementing this effort are the 15 papers by Schneider; by Fahy, by Yung, Proulx and Benichou; by Galea and Gywnne; by Frantzich; by Hokugo, Tsumura and Murosaki; by Charters, Holborn and Townsend; by Bengtson, Holmstedt, Kecklund Lorin and Widlundh; by Bruck and Brennan; by Wright, Cook and Webber; by Horasan and Sinclair; by Fleming; by Brand, Sörqvist, Håkansson and Johansson; by Smith; and by Shao and Murosaki. (The foregoing list is presented in the same order that the papers appear in the proceedings and there is a bias in the selection process to papers with quantitative information that is especially relevant to larger facilities.) Generally, there are many potentially useful data in the proceedings of the 2nd International Symposium on Human Behaviour in Fire and a critical, compilation effort—going well beyond this simple listing—is warranted. That will take some significant motivation and resources which, judging in part from the program for the 3rd International Symposium, do not yet exist anywhere with the possible exception of the Fire Safety Engineering Group at the University of Greenwich. This brings us to the comparable contributions at the 2nd International Conference on Pedestrian and Evacuation Dynamics held at the University of Greenwich. The associated conference proceedings include the following nine papers selected here as especially important, in terms of collecting or organizing data. They are by Irzik; by Daamen and Hoogendoorn; by Thompson, Lindström, Ohlsson and Thompson; by Koss and Brumley; by Miyazaki, Matsukura, Katuhara, Yoshida, Ota, Kiriya and Miyata; by Parke, Gwynne, Galea and Lawrence; by Purser; by Broklehurst, Bouchlaghem, Pitfield and Palmer; and by Kholshevnikov, Shields and Samoshyn. The Pedestrian and Evacuation Dynamics (PED) conference had more papers focused on simulations without much attention to empirically-founded input assumptions. This was partly due to recent growth of attention to modeling evacuation of ships under International Marine Organization (IMO) guidelines.

SUMMARY OF RECOMMENDATIONS MADE REGARDING MODELING AND RESEARCH

Quoting the entire Abstract section of the authors paper for PED 2003:[1]

> Models of pedestrian movement in buildings, in addressing evacuation, should make the most effective use of graphical descriptions of the overall evacuation strategies as well as individual and group behaviour. Group movement models should realistically depict spatial organization of individuals reflecting concerns for territory beyond body envelope. Additional study is needed on basic crowd movement characteristics—density, speed and flow—and their relationship including effect of culture and other context factors. Generally, much basic human performance information should be collected from a variety of contexts. Opportunities abound for documentation and examination of non-emergency pedestrian behaviour which offers many insights that can complement insights gained, sometimes with similar techniques, from studies of emergencies. Modeling skills should also be applied to the most prevalent pedestrian safety problem, that of falls which are problematic for individuals and crowds.

MODELING HIGH-RISE OFFICE BUILDING EVACUATIONS

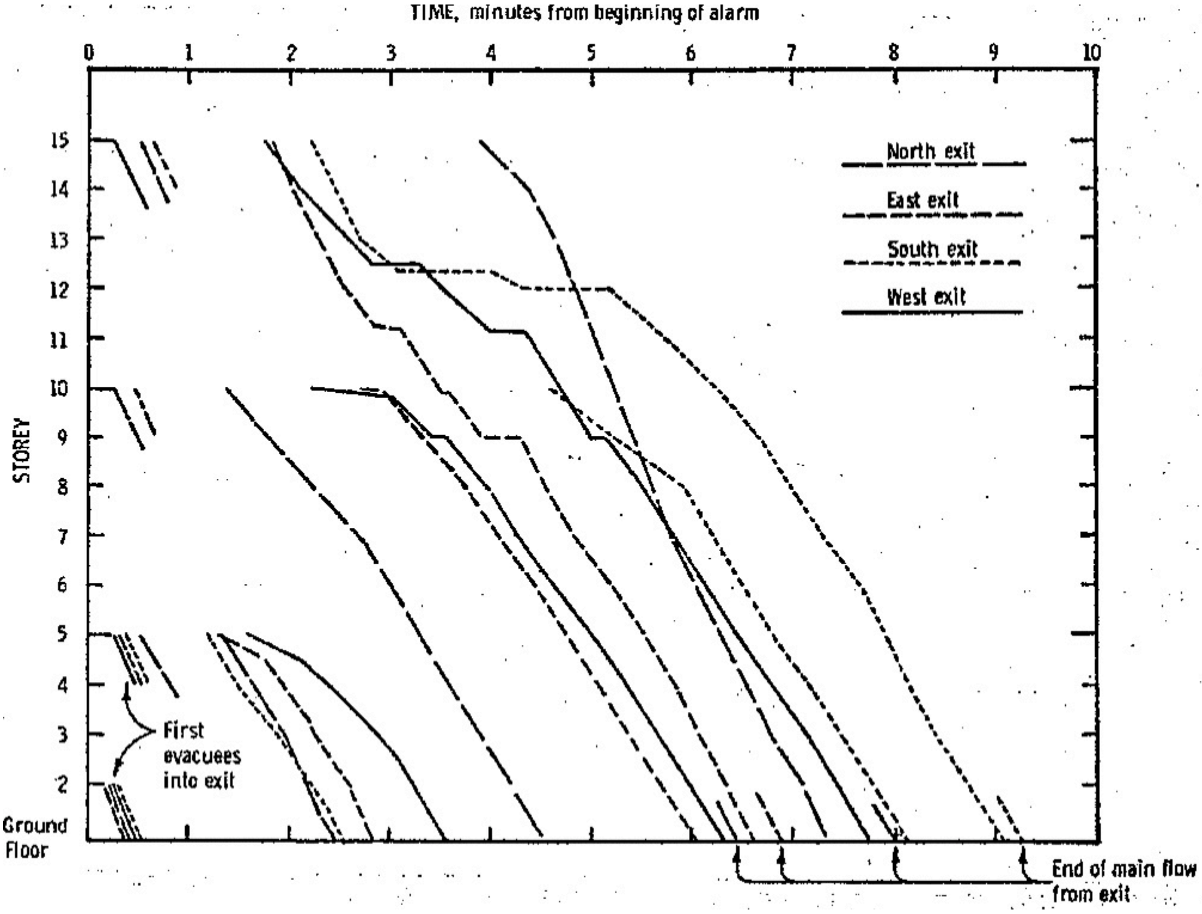
Given the author's disappointment with results—including the format for presentation of data—in preliminary reports and presentations of the World Trade Center (WTC) evacuation study being performed under the US National Institute of Standards and Technology (NIST) research program,[5] attention is drawn once more here to graphical models for evacuation that the author has been using for decades. Use of such models or graphical methods would help to quickly describe the evacuation movement data coming from the NIST study.

Graphical Models of Evacuation Strategies

Early in the Canadian studies of high-rise office building evacuations, from 1969 to 1974, some relatively simple graphical methods were developed to record data from observations of evacuation exercises and describe different evacuation strategies in a way that could be interpreted at a glance.[6] Since the prime focus of the observations was on vertical movement of people on exit stairways over a time scale, the most appropriate charts had vertical height as the Y-axis and time as the X-axis. Traces of individual people's evacuation movement then were horizontal and sloping lines on the chart. Slope of the traces was a measure of speed on stairs. Horizontal spacing of traces was a measure of flow, the number of persons passing a point in a unit time. Vertical spacing of traces was a measure of density, the number of persons in a unit of area.

Figure 1 depicts the entire uncontrolled, total evacuation of the building via four of its five, 1140 mm (45-inch) wide exit stairs. Movement traces are shown for all observers providing location information on continuously running audio recorders. Queuing in the upper portions of two of the stairs was associated with longer egress times due to their larger egress populations (385 and 448 persons). The charts describe the nature of the evacuation generally as well as showing similarities and differences with movement in the four depicted exit stairs. For example, speeds during the stabilized portions of the movement are fairly consistent for all the exit stairs.

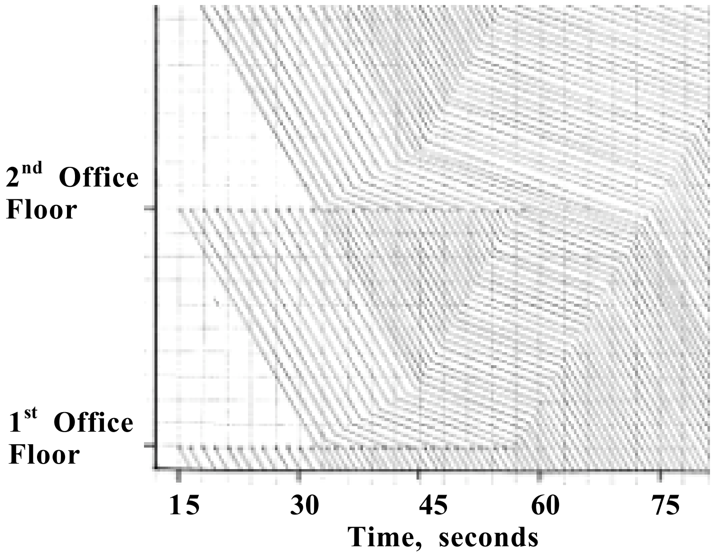
Figure 1: Observer Movement Traces in Uncontrolled, Total Evacuation



Merging Behaviour in Evacuations. As with other uncontrolled, total evacuations observed in the Canadian studies of the late 1960s and early 1970s, there was also a fairly consistent pattern of deference behaviour; people already in the exit stairs allowed people entering the stair from lower floors to proceed first—a behaviour discussed further below. One could also include, in such charts, the traces of every evacuee to see mixing/merging behaviour; this is illustrated in Figure 2. This depicts the exit entry of 29 persons at each of two stories shown and the merging of people from each storey with people coming down the stair on a 2:1 ratio—respectively, 10 persons and 5 persons in 15 seconds. Nominal exit stair width is 1120 mm (44 inches). This precedence behaviour of people entering the exit stair leads to an increasing amount of shuffling speed for people descending from higher floors. The shuffling is shown as the lower slope traces with a speed of about a fifth of that for the higher-slope traces representing a speed of about 0.5 m/s along the stair slope.

The deference behaviour of evacuees at stair entry doors is not an academic phenomenon. It could drastically affect the ability of evacuees from more-endangered upper floors from getting away from a fire, or the smoke migration due to stack effect, impacting the upper floors first. It warrants careful attention.

Figure 2: Traces of Evacuee Movement, Depicting Mixing/Merging at Exit Entry



Such charts are helpful in plotting the position of particular evacuees over time. Because the individual traces for any one stair generally do not cross, but run more or less parallel (unless there is overtaking movement), the charts provide a means of checking or filling in data during analysis. Moreover, it would be useful if multi-floor evacuation simulation models had, as standard outputs, charts such as depicted above in Figure 1. Graphical depictions of individual evacuees—using simplified human figures—have their value, but the charts convey much information that can be assessed in seconds and should not require complex computer programs for presentation. (Additional discussion and depiction of both controlled and uncontrolled high-rise building evacuations are included in the "Movement of People" chapter of all three editions of the *SFPE Handbook of Fire Protection Engineering.*[7])

ELLIPSE MODELS OF PEDESTRIAN MOVEMENT

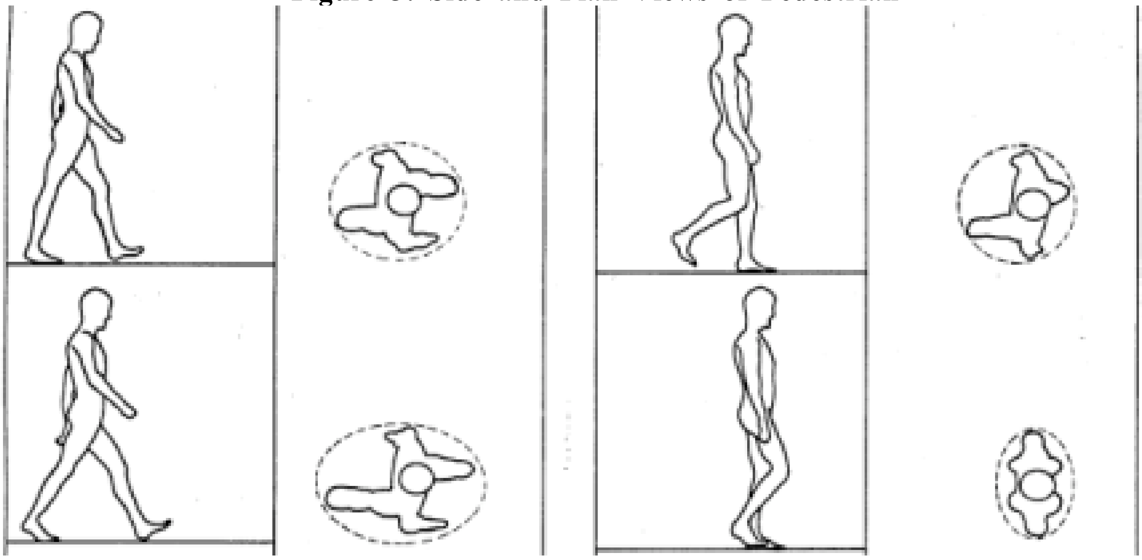
Early models of pedestrian movement, such as presented by U.S. pedestrian movement pioneer, John Fruin, made use of ellipses to represent the plan view of people.[8] While appropriate as a first approximation of human trunk shape (in plan view), the model was most appropriate for very high-density, low-speed conditions. For example, as underlined in the work of both Fruin and Pauls, lateral, side-to-side body sway becomes more pronounced as speed decreases. For conditions where pedestrian density is low—and long strides are possible for higher-speed ambulation, the body changes drastically in shape when viewed from overhead. See Figure 3.

Clearly, only the position shown at the lower right of Figure 3 would fit neatly into the classic ellipse often shown in pedestrian planning literature. For the other stages of the gait cycle (for which only a small portion is shown here), a circle or ellipse oriented in the direction of travel would be the best elliptical approximation of the body plan.

Space

Area taken up by pedestrians increases significantly as ambulation speed increases and this is not simply a function of elongation of the body plan due to outstretched legs. Just as automobile drivers need to increase inter-vehicle spacing as speed increases, pedestrians must do the same. But, beyond some optimum density, pedestrian flow drops as density decreases.

Figure 3: Side and Plan Views of Pedestrian



An extension of Fruin's ellipse model,[8] and ideas about territory bubbles based on Hall,[9] may be helpful in understanding and modeling pedestrian movement as density decreases. This is shown in Figure 4, labeled with number of people depicted. The ellipse model described here reflects a pedestrian's greatly differing concerns—in unidirectional flow (here shown in the upward direction)—about the presence of, and potential interference from, other pedestrian activity directly to the front, to the sides and to the rear. They are, respectively, of high, medium and low priority. At least that is the hypothesis to be confirmed in further examination of this potential model for crowd flow. This ellipse model also begins to take into account some of the criticisms made by Sime in his paper, "Designing for people or ball-bearings?" and of limitations of hydraulic flow models used in simple evacuation modeling.[10]

Figure 4: The Ellipse Model for Pedestrian Movement

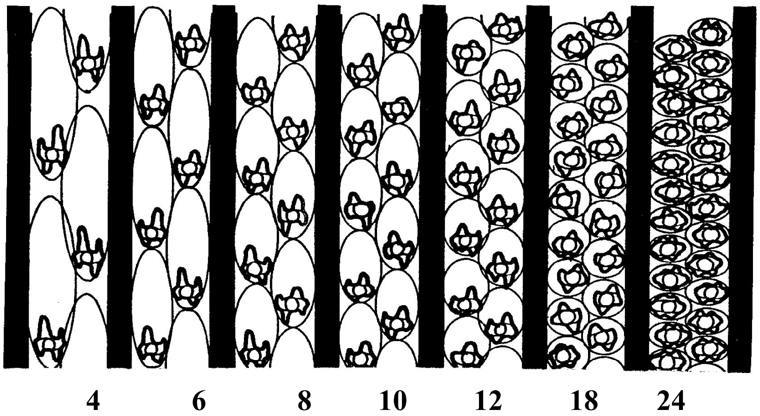


Table 1: Movement Characteristics Depicted in Figure 4 for a Passageway

No. of Persons	Density p/m^2	Speed m/s	Flow p/s
4	0.45	1.3	0.82
6	0.68	1.2	1.14
8	0.91	1.10	1.4
10	1.13	1.00	1.6
12	1.4	0.90	1.8
18	2.0	0.60	1.7
24	2.7	0.30	1.13

HUMAN PERFORMANCE DATA NEEDED

Cultural Factors. Unlike motor vehicle traffic, there has been relatively little observation-based research on pedestrian movement in the varied contexts in which it occurs. Especially notable early work was done in a few countries—Japan, USA and Russia—by pioneers such as Togawa,[11] Fruin,[8] plus Predtechenksii and Milinskii.[12] But there is not a good understanding of how differences in anthropometrics in such countries—let alone complex cultural differences and other social factors—affect basic pedestrian movement characteristics of density, speed and flow. Thus it is unclear how the relatively extensive Japanese research[13] can be applied in other cultures as represented, for example, at the International Conference on Engineering for Crowd Safety in 1993 and in the resulting book, *Engineering for Crowd Safety*.[14]

Emergency and Non-emergency Behaviour. There is ongoing concern among researchers and practitioners about the application—to emergency egress situations—of data, models and insights based on documentation of non-emergency conditions. On the one hand, there is often the thought that, in true emergency conditions, human performance will somehow be much improved, for example, in relation to crowd flow. Some people have assumed that peak flows observed over a period of a minute or less in studies of non-emergency conditions will, somehow, be sustained for long periods—of several or more minutes—during an emergency evacuation. On the other hand, there is the growing awareness—from studies of actual behaviour in emergencies of all types—that participants' real-time perceptions of the situation can be more important than reality, especially the reality that will only be well understood some time after the incident. Thus, emergency evacuation of a large building may be undertaken by large numbers of the total building occupants who are no more aware of the exact reason—and urgency—behind the evacuation than they would be if the evacuation were part of a drill.

Panic. Also, traditional misconceptions about the prevalence of panic and various types of hysterical, confused or antisocial behaviour still persist among many professionals (including journalists) as well as ordinary people. Such misconceptions persist despite repeated research findings showing that panic is rare and, predominantly, altruistic behaviour prevails in emergencies.[15,16] Moreover, journalists' accounts of crowd crush situations too often use the term "stampede" to characterize behaviour that, in reality, is more accurately described as a high-density situation where traffic demand greatly exceeds capacity of some pedestrian element. Researchers are not immune from faulty descriptive terminology; for example, it may well be incorrect to characterize an even as "the spectators rush on the entrance" when, in fact, it is a more gradual build up of density and relatively slow movement. High densities are also especially bad where there are defects in the pedestrian system. Such a defect could be an isolated or a hidden step that can readily cause one or more persons to misstep, lose balance and precipitate a pileup of people who, individually and collectively, lack good information on what is happening and are unwilling or unable to stop moving forward.[17]

Crowd Crush. There are many other tasks for pedestrian modeling. Space available here allows only mention of a few more of these. The role of crowd crush incidents, as a major contributor to life loss and other injuries in buildings for public assembly, needs to be better understood.[14,17] How well can these be modeled? How is crowd crush potential affected by the geometry of a passageway, for example at a 90-degree turn? Also, arching phenomena at doors and other relatively narrow passageways have been studied (with school boys) and modeled (with ball bearings, for example) by Peschl.[19] How realistic are such tests and models for crowd use of doorways? What is the risk of such arches occurring? What is the effect of opening size? What is the role of crowd density? How do individuals in a high-density crowd regard the space around them? How well is it addressed by the ellipse model shown in Figure 4? How does body contact affect people's sense of comfort and safety in dense crowds? What is the role of metering (described as up-stream throttling by Fruin[17]) in reducing the traffic demand for some limited-capacity pedestrian element? How effective is metering as a mitigation measure? What dangers does it add? [17]

Limited Data Base. More empirical data are needed from a variety of contexts. For example, within the USA, current understanding of evacuation behaviour within exit stairways of high-rise office is based largely on studies by Pauls, in Canada over three decades ago, of evacuation drills in buildings that were no higher than 27 floors with evacuation populations no greater than a few thousand.[6] Yet these insights are applied to buildings as high as 110 floors with populations as large as 20,000. For example, the total-evacuation time prediction graphs in the *SFPE Handbook on Fire Protection Engineering*[7] as well as a more-recent, published table[18] are based on evacuation populations of no more than 800 persons per meter of effective stair width; the World Trade Center towers in New York City had evacuation populations of about 6,000 persons per meter of effective stair width in the 1993, post-bombing evacuation (and considerably less, fortunately, on September 11, 2001). Hence we are extrapolating mostly from relatively well-documented evacuation drills of about ten-minute duration to evacuations that can last an hour or more. For this to persist as a temporary measure for decades is not acceptable. More research is needed, especially now that total evacuation is more likely to be used as a mitigation measure in case of emergencies (e.g., from terrorism) and as public attitudes about evacuation are in flux.

Study Opportunities. In addition to performing the best possible, multifaceted studies of what actually happened in evacuations such as at the World Trade Center towers and surrounding buildings on September 11, 2001, we should be doing better documentation of other crowd events where people are “committing data” (the expression first heard from the late John Archea in 1976 during the unprecedented study of spectator behaviour at the Montreal Olympic Games). For example, at a minimum, images from strategically placed video cameras in exit stairs—such as the cameras commonly installed for security reasons—should not only be monitored at the building’s emergency control station; they should be automatically recorded (at the highest quality possible) on-site and remotely during evacuations of all kinds. The 25 or 30 images per second from video coverage of even a single, complete stair flight can be easily analyzed to provide flow, density, speed and crowd configuration information. Depending on the image quality, it might also be possible to identify specific individuals so that a time reference is available for use with other video records or interview information as well as to identify those successfully evacuating. Of course the most basic, essential information about an evacuation will be available almost immediately with minimal analysis—that is the exact time scale for the egress and the number of evacuees.

Actual Building Populations. Remarkably, many months after “9/11” we relied on the estimate by a journalist, albeit an excellent one, of the actual population present in the two World Trade Center—about 5,000 to 7,000 people per tower—at the time of aircraft impact.[19] Thirty months after Dennis Cauchon’s estimate of December 2001 (in *ÛSA Today*) the National Institute of Standards and Technology (NIST) come up with more-carefully researched estimates of the actual population on the morning of 9-11. NIST’s estimates were 8,900 (±750) for WTC 1 and 8,500 (±900) for WTC 2. Even more remarkably, eleven years after the earlier emergency evacuation of the World Trade Center towers in 1993, we still have researchers’ estimates of that evacuation population differing by a factor of about two.[5,18,20] Thus, in their June 2004 reports on the WTC evacuation, NIST researchers reported 25,585 as the “typical full capacity with visitors” of each WTC tower and then used that to estimate a minimum, total evacuation time, with stair use only, of nearly 140 minutes. Even more questionable, they used the multiple of 2.5 (based on the ratio of the very high “full capacity” population to that on 9-11) to estimate that “a full capacity evacuation of the WTC towers with 25,000 people would have required 4 hours”—2.5 times more than 100 minutes reportedly required on 9-11. More care should be taken with such estimates of actual building populations.

Minimum Stair Width. Data are needed—and readily obtained from the recommended camera systems—for example on the relative merits of various stair widths for mass unidirectional flow, overtaking movement, plus counter-flow movement of evacuees and first responders (such as occurred extensively in both the 1993 and 2001 evacuations of the World Trade Center). Two widths need to be compared as soon as possible. (Apparently the WTC evacuation studies by NIST are not delving into exit stair use ergonomics as much as this author had hoped.) One width is the widely used, traditional minimum, code-credited, nominal width of 1120 mm or 44 inches (based on the now-discredited, 560 mm or 22-inch units of exit width) which effectively provides only about 940 mm or 37 inches clear between handrails. The other is the better justified, but not yet widely used width providing 1200 mm or 48 inches clear between handrails (corresponding to a nominal, code-credited width of about 1400 mm or 55 inches).

Each of the two World Trade Center towers had two exit stairs with the first width and one central exit stair with the latter width. The few available photographs (by John Labriola) of the exit stair evacuation on "9/11" were taken in the narrower-width exit; they clearly showed the significant inadequacy of the traditional, 1120 mm (44-inch) nominal width for counterflow of firefighters and evacuees (who had to stop and twist to the side during the counterflow). Earlier studies by Pauls had clearly demonstrated that two-abreast, unidirectional movement was very rare with the traditional 1120 mm nominal width.[21] Lateral body sway (due to alternation of the weight bearing foot), which increases as ones speed is reduced, is a prime reason for the predominately-staggered configuration of crowds on stairs (as well as other pedestrian facilities). How well is such body sway modeled in pedestrian movement simulations? Finally, if stair widths are increased for new building exits, what does this mean for the width of discharge doors? Should they be wider than the conventional 900 mm (36 door)? Should there be a move toward use of two doors at the exit discharge?

Deference Behaviour. Another important class of information to be collected from evacuations of large, multi-floor buildings would describe deference behaviour occurring when descending evacuees in an exit stairway meet other evacuees attempting to enter the exit from a lower floor. Who defers to whom? What affects such deference behaviour? How can such deference behaviour be altered or managed to make sure that the most-endangered building occupants are given priority in their evacuation? In fires in high-rise buildings, generally those above the fire floor are more endangered than those below. Yet, in Pauls' early documentation of uncontrolled, total evacuation drills in Canadian office buildings, evacuees already in the exit stair generally deferred to those entering from floors below them. This is shown in Figure 2 where, over a period of 15 seconds, there are only five persons from the descending flow merging with ten people from the incoming flow. This impedes the flow of persons from higher floors. Indeed, for evacuation populations larger than modeled in Figure 2 (29 persons per floor per stair), the deference behaviour will lead not only to shuffling speeds but complete stoppages—of increasing duration for higher floors—for people already in the exit. For the relatively small high-rise building depicted in Figure 1, the most crowded of the building's four egress stairs had queuing and shuffling movement lasting for a few minutes of the 9-minute total evacuation time. (Its 1140 mm, 45-inch, nominal width served 448 evacuees.) For very large buildings, such as the World Trade Center, queuing of upper-floor evacuees could last 60 minutes during a total, 100-minute evacuation time.

How well do we understand such deference behaviour and its management? How well do we model it? Do our models realistically describe the social behaviour at exit entrance doors, for example, taking into account that evacuees are often part of small clusters that should be kept intact during an evacuation? How can models be used to help describe this phenomenon to ordinary building occupants to better prepare them to perform best during an evacuation? (This would appear to be one of the strengths of rich, real-time graphical output displays with models such as EXODUS.[22]) When there is a stoppage of flow on the stairs, how fast does that stoppage proceed up the stair? Depending on the relative densities of moving and stopped evacuees, the speed of stoppage and of resumption of movement proceeds at some predictable speed. In figure 2, that upward-progressing transition is assumed to move mostly at 0.5 m/s, similar to the descent speed of freely flowing evacuees (expressed here as the slope speed).

Demand Issues and Code Requirements. Yet another topic for examination is the influence of traffic demand on mean flows. The "Effective-Width Model" and associated equations provided by Pauls (within the "Movement of People" chapter of the *SFPE Handbook of Fire Protection Engineering*) describes an unexplained phenomenon of slightly increasing mean flow with total number of persons evacuated.[7,21] That is, with increasing evacuation population demand, higher flows occur. This affected some egress capacity rules in US model building codes and national standards, especially NFPA 101, the *Life Safety Code*, beginning in 1988. Under this arrangement, the peak flow was assumed for the least-demanding egress stair capacity rule in US codes and standards, requiring only 1.5 mm (0.060 inch) of nominal egress width for each person in a "Smoke-Protected Assembly Seating" facility serving, within a single assembly space, 25,000 or more seats. This rule permits a total of 933 persons to use a 1400 mm (55 inch) wide, nominal width stair. Pre-2003 editions of NFPA 101 provided (within the table of required egress widths per person) estimates of minimum, "Nominal Flow Time."

Demand and Flow. For the most intensively used stairs, such estimates were for a minimum flow time of 600 seconds which compared with more-traditional flow time estimates of 200 seconds, applied to facilities up to 2,000-seat size, where 7.6 mm (0.3 inch) of nominal stair width was provided per person (or 184 persons for a 1400 mm width). Thus the range of assumed *mean* flows for a 1400 mm nominal width stair is from 0.92 p/s to 1.56 p/s, representing a 1.69 increase in assumed egress flow performance when the population demand is increased by a factor of 12.5. We need better field validation and modeling of such assumptions than what came from Canadian studies between 1969 and 1976 (including the office building evacuation drill observations[6,7,21] and many unpublished observations of crowd flow in large assembly facilities such as those used for the 1976 Olympic Games in Montreal).

Falls. Thus far the intensive focus on egress modeling (in this paper and in the fire safety field generally) has given short shrift to the leading cause of injuries in buildings. It is not fires or other disasters. Falls are the leading cause of injuries. For the USA, even injuries from falls on stairs exceed civilian fire injuries by a factor of about 40; generally injuries from falls exceed those from fires by two orders of magnitude. Comprehensive or societal injury costs for stair-related falls have been estimated to be on the order of $50,000,000,000, for the year 1995, in the USA.[24] For all falls occurring in the USA, the 2002 medical care costs alone were about $25,000,000,000 and such costs make up only about 10 percent of comprehensive (societal) costs. Modeling falls—and the missteps that lead to falls—is an important task that pedestrian movement modelers should at least be aware of if not directly involved in development of such models. A misstep is a departure from normal gait. A misstep could include a trip, a stumble, an air-step, an over-step, an under-step, and a slip. Some, like an air-step—the especially jarring footfall that occurs when a person is expecting a continuation of a level walking surface but experiences, instead, a drop of a few or several inches—can cause injuries even if the person does not fall as a result. (Ones body cannot react to the unexpected drop for heights less than about 180 mm or 7 inches.) Thus missteps and falls are essential considerations for both individual movement and crowd flow. Although slipping in pedestrian gait has been extensively studied, other misstep scenarios—that are much more prevalent on stairs—are relatively under-researched and inadequately modeled.[25]

Handrails. Neither has there been much research into fall mitigation where a person grabs for a handrail. The work of Canadian biomechanics researcher Brian Maki and his colleagues is a notable exception for handrail functionality including the critical behaviour of grabbing for a handrail to arrest a fall.[26] Handrails are important pedestrian aids for both buildings and ships, especially where elevation changes— even small ones—must be made obvious as well as to be successfully traversed.

Stair Safety and Usability. Even the longest-running debate in stair design and standardization—the issue of step geometry—has been subjected to relatively limited scientific study. Recent research directed by Mike Roys at the UK Building Research Establishment, on subjective and objective measures of usability and safety for various stair going (tread run) geometry (150 mm to 425 mm or 5.9 to 16.7 inches), is providing valuable insights for both dry and slippery treads. The focus of this work has been the movement of individuals; implications for crowd movement are thus far based on skimpy evidence although the "Emergency Movement" chapter of the *SFPE Handbook of Fire Protection Engineering* as well as model codes and national standards in the USA have attempted to take step geometry into account in setting egress flow performance and capacity criteria.[27] Much better empirical study is required on this.

Population Characteristics. Certain circulation features—especially stairs—present special challenges for older adults, people with disabilities and younger children.[18,24] How well do our building design standards as well as our models of human performance address them? Overlapping the author's preparation of this paper is another writing task—preparation of a chapter on children and stairs for a book on children and ergonomics; the literature for such a chapter is sparse as is the literature on children and egress. Also, in addition to being conscious of varying capabilities over the age spectrum and due to disabling injury or disease, we should pay attention to the social nature of evacuation and responses to emergencies generally, a topic extensively addressed by the late Jonathan Sime for example.[10] How well do our models of egress address family members' roles and social affinity generally—in addition to differing physical capabilities?

Finally, regarding population characteristics, we should try to determine how the increasing prevalence of obesity and lack of physical fitness affects not only the design of exits but our evacuation procedures. Here it is interesting that an estimate of three percent was made by the author 35 years ago about proportion of typical office building populations who might not be in a good position physically to evacuate down stairs with other evacuees, especially in crowded conditions with limited possibility of stopping for rests. Early indications from the World Trade Center evacuation study suggests that such an estimate should now be higher, perhaps even twice as high to account for not only our taller buildings but also the decreasing physical capability of their populations.

CONCLUDING REMARKS

There are more questions raised than answers provided in this incomplete, brief, eclectic examination of evacuation and other movement in buildings. Intended to be thought provoking, it is based on decades of one person's experience—*and treasured peer contacts*—in research, consulting and codes/standards development. With so much personal effort devoted in recent years to ever-broader codes/standards development activities, there has been too little contact with the exciting field of pedestrian movement studies including computer-based modeling. Thus, participation in PED 2003 was highly valued. It reinforced long-held views that we needed a better empirical basis for not only our conventional standards and codes but for the models that are increasingly used as part of performance-based codes. It also reinforced the dangers of evacuation modelers being seduced by their computer models. It is possible to fall in love with ones model. The small, moving figures on the computer screen can be especially seductive. We should always try to make sure that the models reveal much more than they conceal. Revealing or raising questions is especially healthy.

Generally, we should devote at least a comparable amount of effort and resources to repeatedly observing, documenting and studying actual pedestrian and evacuation behaviour. The overhead, plan view of individuals and crowds is an especially fascinating, valuable one for study purposes Also, examining high-quality film and video records of individual movement and crowd behaviour at various playback speeds—very slow through very fast as pioneered by cinematographer Ron Fricke in the Francis Ford Coppola film, "Koyaanisqatsi" ("life out of balance")—is also fascinating and very instructive.[28] Real people, individually and in groups, will always be more fascinating and instructive than will be even our best mathematical abstractions and depictions from computer simulations and other models.

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