# Dependence of Modelled Evacuation Times on Key Parameters and Interactions

DAVID PURSER
Hartford Environmental Research, Hertfordshire, UK.

**ABSTRACT**

Times and patterns of buildings evacuations involve interactions between many behavioral parameters reflected in the increasing complexity of computer simulations. A combination of detailed GridFlow computer evacuations simulations, calculation models and experimental evacuations have been used to determine the extent to which evacuation patterns and times are largely dependent upon a small number of key parameters and interactions. Cases investigated included a single retail enclosure and multi-enclosure, multi-storey office buildings designed following UK prescriptive guidance. It is concluded that evacuation times are very dependent upon a small number of critical factors (including pre travel activity time [PTAT] distributions, exit choice ratios, maximum flow rates, merge ratios, and densities of stationary and moving groups). Even sophisticated computer simulations can give misleading results if these factors are not adequately represented.. while simple calculation methods can provide a useful first estimate of evacuation times for designers, and a useful check on the performance of more complex simulation models.

**KEYWORDS:** modeling, human behavior, performance-based design, human factors, response patterns, egress, evacuation, merge ratio

## INTRODUCTION

Early attempts to estimate evacuation times for building spaces based upon simple flow calculations or hydraulic computer models have largely given way to increasingly complex modelling simulations incorporating larger numbers of behavioral and physical movement parameters and their interactions [1-5]. These parameters are generally validated against experimental data, but it is not always easy to determine that they are adequately represented in the models. It may also not be obvious which parameters have only a marginal influence on outcomes (while requiring considerable effort in terms of input data and computational power) and which are major determinants of escape times. If outcomes such as total evacuation times for single enclosures, or for different individual enclosures in multi-compartment buildings, can be shown to depend mainly on a small number of critical parameters, then it may be possible to obtain reasonably accurate evacuation time estimates by using simple calculation methods. These could then be useful for preliminary stages of a design or for review/validation of more complex modelling simulations [6]. It also follows that if any of the critical parameters are ignored or inadequately handled in the simulation, then escape times and evacuation patterns may be flawed.

In experimental evacuations it has been found that evacuation times for single enclosures are very dependent upon the interactions between the pre-travel activity time (PTAT) distributions of the occupants and the travel-related features determining physical movement to and through the exits [1,7,8]. (PTAT [also know as pre-movement time] consists of the interval between the time when a warning is given and that when the first move is made by an occupant towards an exit. For groups of occupants, PTAT follows a distribution. In most cases this consists of a variable delay before the first occupants start to move towards the exits followed by an approximately log-normal distribution of starting times until the last few occupants begin to move [7]. Travel time parameters include exit choice, the distance between each occupant and their chosen exit, occupant densities, unimpeded and impeded movement speeds and flow rates through the exits. However, it is considered likely that for crowded cases the most important characteristics are likely to be the PTAT of the first few occupants to move and form queues at the exits, while for sparsely occupied spaces (or very wide PTAT distributions), the PTAT of the last few occupants to move, walking speeds and travel distances to the exits are likely be the dominant factors [1,6,9,10].

For multi-storey buildings a second set of variables is introduced involving the merging flows of occupants from each occupied enclosure into and through the escape routes and stairs. These impact not only on the time for total building evacuation, but when escape routes become congested, they can affect the clearance times for each individual enclosure. For multi-storey evacuations, involving simultaneous evacuation into

FIRE SAFETY SCIENCE–PROCEEDINGS OF THE NINTH INTERNATIONAL SYMPOSIUM, pp. 353-364

a protected stair of a number of floors, additional important parameters include the merge ratio at storey exits and occupant densities on the stairs. Merge ratio data are sparse, but three main assumptions used are:

- Flow dominated by occupants on the stair - building empties from the top floor down
- Occupants on the stair "defer" to occupants at storey exits - building empties from the bottom up
- Merge ratio (around 50:50) at storey exits – building empties from the bottom up.

In order to examine the dependence of modeled evacuation times for a single enclosure and multiple enclosure buildings on key parameters, example cases have been examined for a single enclosure retail space and a 10-storey office building with two lobby-protected stairs. For the single enclosure case, the evacuation times for different occupant populations were estimated using three methods consisting of:

1. Detailed computer evacuation simulation using (GridFlow) [1]
2. Spread-sheet calculation method using the full PTAT, travel speed, travel distance distributions and maximum exit flow rate capacities.
3. Simple calculation using the 1st and 99th percentile PTAT times, average travel speed and travel distance, and maximum exit flow rate capacities

For multi-storey (or other multi-enclosure) buildings, simple methods are also used for calculating total evacuation times. But while estimation of clearance times for individual floors has been carried out using a spreadsheet model, computer simulations are more flexible and easy to use, providing more detailed simulation results. For this study a series of GridFlow computer simulations were carried out to examine the effects of, and interactions between, different variables. For all simulations key individual simulation parameters and outcomes of total runs were partially validated against experimental data.

This paper examines the dependence of modeled evacuation times on key parameters, their interactions and their sensitivity to variations in these parameters. It underpins previously reported work identifying wider aspects of critical evacuation factors and the application of egress models to fire safety engineering design cases [6]. Some Figures presented in this paper were used previously as illustrations of key aspects. This paper details the specific work used to produce those and introduces and discusses in detail other key findings.

## METHODS

### Evacuation of a single rectangular retail enclosure (2000 m$^2$)

To examine the dependence of modeled evacuation times for a single enclosure on key parameters, an example case was set up using a simple generic square retail space (sides 42.4 m , direct travel distance 30 m) with 4 available exits [1.125 m width]). The maximum direct travel distances, exit widths and design

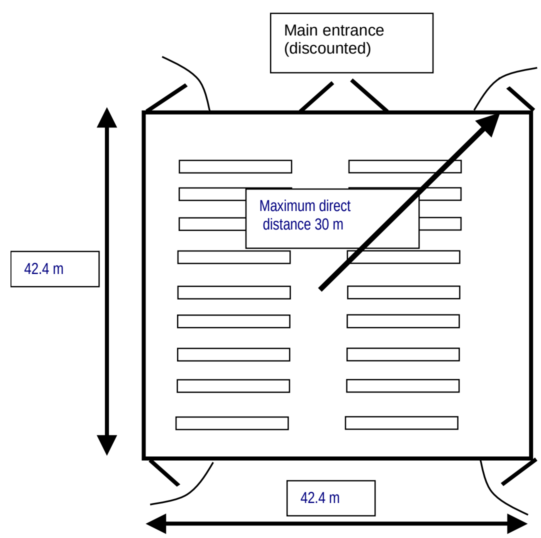



Fig. 1. Generic retail enclosure

population of 900 were set according to the UK prescriptive guidance and the space was divided with rectangular racking as in a supermarket. For the PTAT distribution, the data obtained from an experimental monitored evacuation were used [7,11]. The evacuation times for different occupant populations were then estimated using the three methods listed above. For all methods it was assumed that each occupant left by their nearest exit, although effects of exit choice variations could be accounted for simply for each method.

For the first method, 10 detailed repeat evacuation simulations were carried out using GridFlow for several different occupant populations, with all individual occupant locations and other parameters randomly assigned from defined distributions for each run. Outputs included PTAT distributions and numbers of occupants remaining with time. Within GridFlow each occupant was randomly assigned a PTAT time for each simulation run from a log-normal representation of the PTAT distribution. Occupants then moved to towards their nearest exit taking the shortest path avoiding obstructions, their individual travel distances depending upon their specific starting location. Travel speed towards the exit then depended upon their unimpeded movement speed (randomly derived from a set normal distribution) or the proximity of other occupants (crowd density) at each step in the simulation. Flow through the exits also depended on speed and density, but was capped for each exit at the maximum flow rate according to Nelson and Mowrer [12,1]. Default (unimpeded) walking speeds are assigned from a theoretical normal distribution (mean of 1·19 m/s and a standard deviation of 0·3 m/s, subject to a minimum of 0·3 m/s). This mean was derived from Nelson & Mowrer [12]. The model allows for overtaking of slow individuals by those moving more rapidly, if space allows. Further details of the model are provided in [1].

For the second method, the space was randomly populated with individuals, each of whom was randomly assigned an individual PTAT time and unrestricted walking speed from the distributions. The time at which each occupant presented themselves at an exit was calculated from the distance to the nearest exit (avoiding obstructions) and unrestricted walking speed. The frequency distribution of presentation rates (persons per second presenting at the exits) was plotted and compared with the maximum flow capacity of the exits to determine the time to queue formation. The estimated evacuation time was then calculated as the time to queue formation plus the total exit flow time for the population. For low occupant populations evacuation time was given by the 99$^{th}$ percentile PTAT plus walking time distribution.

For the third method evacuation times were calculated using the following simple expressions:
For a crowded case - The evacuation time for an enclosure ($\Delta t_{evac}$) is given by:

$$\Delta t_{evac} = \Delta t_{pre(1st\ percentile)} + \Delta t_{trav\ (walking)} + \Delta t_{trav\ (flow)} \quad (1)$$

$\Delta t_{pre(1st\ percentile)}$ = time from alarm to movement of first few occupants
$\Delta t_{trav\ (walking)}$ = walking time (the unimpeded average walking speed x average travel distance to exits [a more conservative estimate uses the maximum direct travel distance]).
$\Delta t_{trav\ (flow)}$ = time of total occupant population to flow though available exits.

For the sparsely occupied case - Evacuation time from an enclosure is then given by:

$$\Delta t_{evac} = \Delta t_{pre(99th\ percentile)} + \Delta t_{trav\ (walking)} \quad (2)$$

$\Delta t_{pre(99th\ percentile)}$ = time from alarm to movement to time of movement of last few occupants (= time to first percentile plus time from first to 99$^{th}$ percentile)

**Evacuation of a multi-enclosure building (up to 10-storeys served office buildings)**

These simulations were intended primarily to investigate flow patterns from each floor and in the stairs, and in particular to estimate minimum floor clearance times into the protected stairs, so PTAT times were set to zero. Evacuation times therefore represented the minimum achievable for the physical building and escape route dimensions, assuming an instant response from all occupants. The simulated buildings (designed and populated according to UK prescriptive guidance [13]) consisted of 4 to 10-storeys served rectangular floor plan office buildings with two lobby-protected stairs at each end (open plan floor area 1440 m$^2$ [53.7 x 26.9 m] maximum direct travel distance 30 m. It was assumed that all occupants evacuated to their nearest stair, so modelling was restricted to a single stair and the “half” floor it served. For the fire floor one exit was assumed to be blocked so that the entire population on that floor used one exit and stair. The evacuation strategy was simultaneous for the whole building, using a storey exit width of 1.05 m and a stair width of 1.3 m. The population evacuated (non-fire floors) was determined according to ADB Volume 2 Table 7 [13], ranging from 102/ floor for 4 storeys served to 71/floor for 10 storeys served.

The stair used as a model was a typical escape stair, with a standing area available between floors of 14.7 m$^2$, consisting of 2 flights, one mid-landing and a lobby landing between each pair of floors. In the model the occupant density was set to either 2 or 4 persons/m$^2$, giving an occupant capacity of 29 or 59 persons.

## RESULTS

### Evacuation of single rectangular retail enclosure (2000 $m^2$)

PTAT distributions are input variables for evacuation simulations since they cannot be modelled directly, and constitute critical evacuation factors for the application of egress models [6]. For these simulations the PTAT distributions were derived from the distribution obtained experimentally in a monitored evacuation of a retail store [7,11]. In this case the first occupants began to move almost immediately after the general alarm was sounded, with a PTAT of ~8s. This was followed by a distribution of individual PTAT times up to approximately 2.5 minutes. The individual PTAT times for each simulation were sampled according to a log-normal distribution curve fitted to the experimental data [1].

Figure 2 shows full GridFlow evacuation simulation results for different occupant populations. Also shown is the N & M [Nelson and Mowrer [12]) curve, which represents the minimum possible calculated flow time for the enclosure, with optimum exit usage from the moment the alarm was sounded, assuming zero PTAT times and a constant maximum flow rate of 80 persons/min/metre effective width. The lower two horizontal broken lines on Fig. 2 show the theoretical 95$^{th}$ and 99$^{th}$ PTAT of 95 and 114 seconds, which are constant for the given distribution. The three lines with symbols show the times required for 95%, 99% and last out from full computer simulations (using GridFlow) for all individual occupants, taking into account all interactions (including impeded travel) for different populations (average of 10 simulations for each point). For the design population of 900, the minimum flow time exceeds the 99% PTAT and presentation time limits by 95 and 82 seconds. To test sensitivity to PTAT, the full simulation was run with "stretched out" PTAT distributions, with the basic lognormal shape was preserved, but assuming that (due to less efficient management and a less alert population) the whole distribution was lengthened by factors of up to 3.5. Figure 3 shows no increase in 99$^{th}$ percentile evacuation time until the distribution was more than a factor of 2 wider; i.e. that the overall time for the population to respond was twice as long.

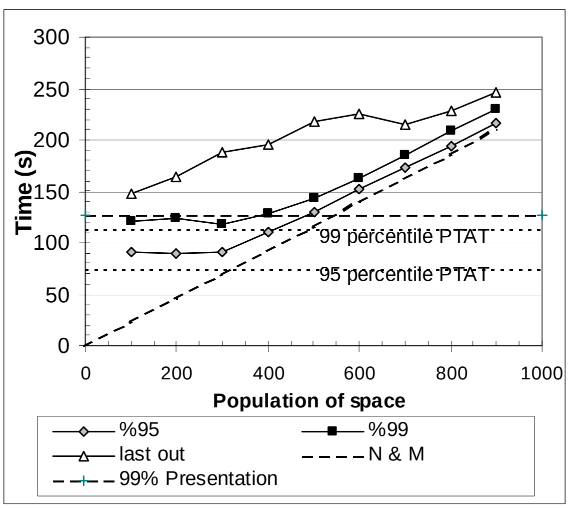



Fig. 2. Phases of evacuation times for different populations in a square retail enclosure using the measured PTAT distribution.

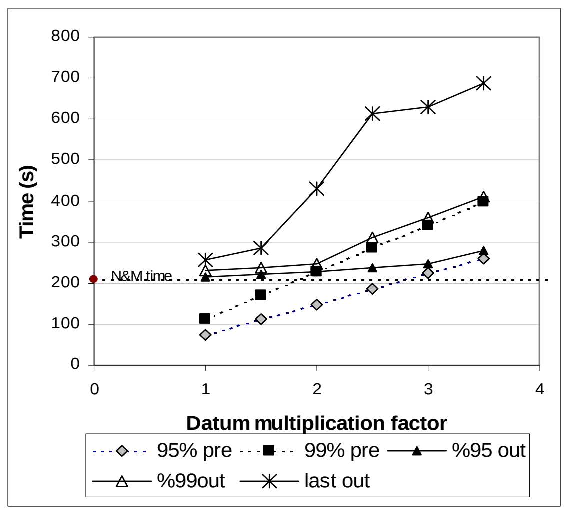



Fig 3. Effect of different extended PTAT distributions

Full GridFlow simulations for a prescriptively designed enclosure with an area of 18,000 $m^2$



Two concepts found to be useful are "walking time" and "presentation time". Walking time is the time for each individual to walk from their starting location to their nearest exit, assuming a walking speed unrestricted by crowding effects. Presentation time is the time each individual presents themselves at the exit ready to walk through (assuming an infinite exit flow capacity), given by their PTAT + walking time.

At high occupant densities, once the first few occupants begin to move, the evacuation is limited by the physical exit dimensions plus a small period for queue formation. For occupant numbers of <~ 1/3 of the design number, evacuation time depends on the PTAT of the last occupants to move, so approaches the 95 and 99 percentile PTAT times plus a small constant. The 99$^{th}$ percentile line plus a figure for average walking time of 14 seconds provides an exit presentation time of approximately 128 seconds, shown as the upper broken horizontal line, representing the minimum time required to evacuate assuming unimpeded movement. The separation between the Nelson & Mowrer time and the actual 99% evacuation time provides an approximate estimate of the time to queue formation of 20 seconds, which represents the presentation time of the first few occupants. The PTAT and walking times of the rest of the population after 20 seconds have no effect on the evacuation time of 99% of occupants.

For the second method it was necessary to obtain the full PTAT, travel speed, travel distance distributions and maximum exit flow rate capacities. The maximum flow rate was calculated from the summed effective widths of the available exits and the maximum specific flow rate of 80 persons/metre effective width/ minute. Each individual was randomly assigned a location (and hence a travel distance), a PTAT time and unrestricted travel speed from the distributions. These were derived using the spreadsheet, but could also be derived using GridFlow (but without the movement simulation phase). Walking time was calculated for each occupant by multiplying the travel distance to the exit by their individual walking speed. Adding each individual walking time and PTAT time then gave the "presentation time" for each

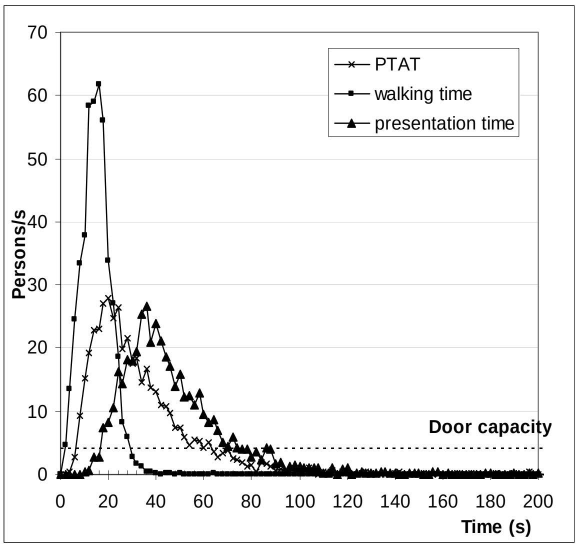



Fig. 4. PTAT, Walking time and presentation time for the 900 occupant design maximum case

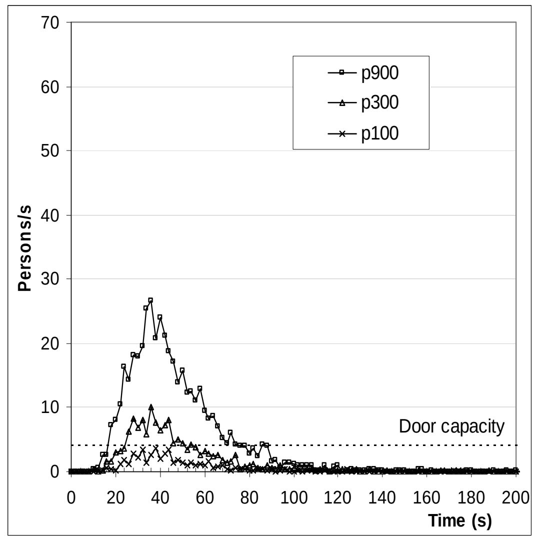



Fig. 5. Presentation time distributions for three different occupant populations



occupant. Figure 4 shows the distributions generated by the spreadsheet for PTAT, unrestricted waking time and presentation time for the 900 occupants case (the "crowded" prescriptive design maximum case). The horizontal line shows the maximum door flow capacity. A key time point is that when the rate of occupant presentation at the exits exceeds the door flow capacity. From this point queue formation occurs, and the additional time required to clear the space is then assumed to depend simply on the calculated minimum flow time for the occupant population of 900. For this case, the time to queue formation is 19 seconds and the flow time is 210 seconds, giving a calculated 99$^{th}$ percentile evacuation time of 229 seconds. Figure 5 shows the calculated presentation time distributions for three occupant populations. For a population of 100 (sparsely occupied case) the presentation rate never exceeds the door flow capacity, so it is predicted that evacuation of this population would depend upon the 99$^{th}$ percentile presentation time (99$^{th}$ percentile PTAT + walking time), while for the 300 occupant case queue formation is predicted for a short period. For a population of 200, the calculated 99$^{th}$ percentile presentation time is 126 seconds. This method represents a simplification of the full computer simulation in that it ignores: effects of crowding on walking speeds as occupants approach the exits, behaviours such as overtaking, and occupants passing through the exits before queue formation is established. Ignoring crowding slightly underestimates the evacuation time, but ignoring evacuation before queue formation slightly overestimates evacuation time.

Table 1 compares the predicted times for all three methods for the crowded (900 occupants) and non-crowded cases (200 occupants). When the results of the second (spreadsheet distributions) method were compared with the detailed GridFlow analysis (full computer simulation) for the design population of 900, the calculated 99$^{th}$ percentile evacuation time of 229 seconds (derived from time to queue formation [19] [19 seconds] plus the calculated exit flow time for the occupant population [210 seconds for a population of 900]), was very close to the figure of 230.1 (s.d. 4.4) seconds predicted by the detailed GridFlow simulation. For 200 occupants, (where queue formation did not occur), the calculated 99th percentile presentation time (126 seconds) was close to the modelled 99th percentile evacuation time (123 s.d 17.7).

Table 1. 99th percentile evacuation time predictions using three methods

| Numbers | Full simulation | Distributions | Simple calculation |
|---|---|---|---|
| 900 | 230 s.d. 4.4 | 229 | 232 |
| 200 | 123 s.d.17.7 | 126 | 128 |

For the third (simple calculation) method, the PTAT of the first few occupants to move (1st percentile) was determined from the PTAT distribution (in this case 8 seconds). Average unimpeded walking time, was obtained from average unimpeded walking speed (1.2 m/s) multiplied by the mean travel distance. This was determined by averaging the travel distances for a randomly dispersed population. It was possible to estimate travel distance in three different ways. The simplest and most conservative might use the maximum direct travel distance for the enclosure. Another estimate could be based upon the averaged x-y coordinate travel distances for a randomly dispersed population in the unobstructed enclosure, while the most accurate estimate (that used) takes account of the effect of obstructions on actual travel distances.

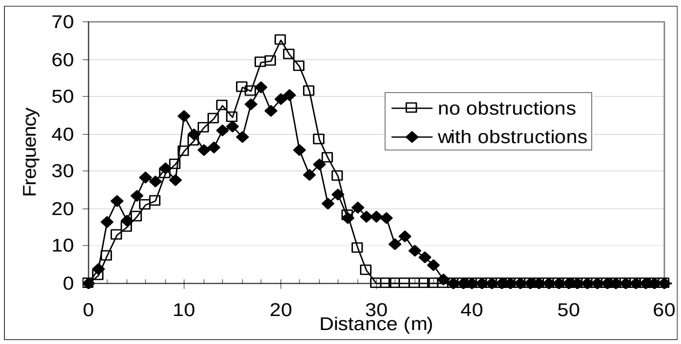



Fig. 6. Distributions of travel distances to nearest exit for a randomly dispersed population in the enclosure shown in Fig. 1 with and without obstructions

Individual travel distances constitute one of the pre-simulation outputs from GridFlow, and Fig.6 shows plots for the sample case with and without obstructions. The presence of obstructions has little effect on mean or median travel distance, although individual travel distances exceed 30 metres for some occupants.

For this method the mean travel distance (17 metres – with obstructions) and the average unimpeded walking speed (1.2 m/s) gives an average walking time of 14 seconds, which when added to the 1st percentile PTAT of 8 seconds gave a 1st percentile presentation time of 22 seconds. Added to the calculated exit flow time of 210 seconds this gives a calculated 99th percentile evacuation time of 232 seconds compared to 230.1 (s.d 4.4) for the full simulation. For 200 occupants the calculated evacuation time of 128 seconds (1st+99th percentile PTAT 114 + 14 seconds walking time) compares with the full simulation figure of 123 s.d 17.7. The further simplification of using this method is that the PTAT and walking times of the first occupants to present at the exits could differ somewhat from the mean values used. However, as shown in Table 1, the 99th percentile evacuation times calculated without carrying out computer simulations, using either individual data distributions or simple average values, are very close to the results obtained using the detailed GridFlow simulations, and within the standard deviation of 10 GridFlow runs.

It is concluded that for simple single enclosures, evacuation times can be calculated accurately using simple constants for PTAT and walking time (calculated from average travel distance and unimpeded walking speed). Relatively small errors are introduced by not to using detailed computer models, taking into account the full distributions of variables for individual occupants. The key determinants (for both simple calculations and models) are the PTAT of the first and last occupants, estimated from available data for similar scenarios [9,10], average walking time to the exits and the maximum flow capacity of the exits.

**Sensitivity analysis for single enclosure case**

This analysis has demonstrated the importance of certain key variables in the determination of evacuation, and the lesser importance of others, but another issue is the extent to which uncertainties regarding some of the important variables may affect predicted evacuation times. Arguably the greatest uncertainty for any particular design case is the precise shape and time distribution of the PTAT distribution. A number of further additional GridFlow runs were carried out to examine the effects of PTAT variables. One issue is the sensitivity of the evacuation time to the width and shape of the PTAT distribution, which might vary for any one behavioural scenario depending upon factors such as staff performance on a particular day. In practice the experimental PTAT distribution used represents a very well managed case, with a very short initial response time and a narrow distribution of subsequent starting times. The “stretched out” PTAT distributions in Fig.3 showed there was no increase in 99th percentile evacuation time until the distribution was increased by more than a factor of 2, which provides a measure of the sensitivity to this parameter.

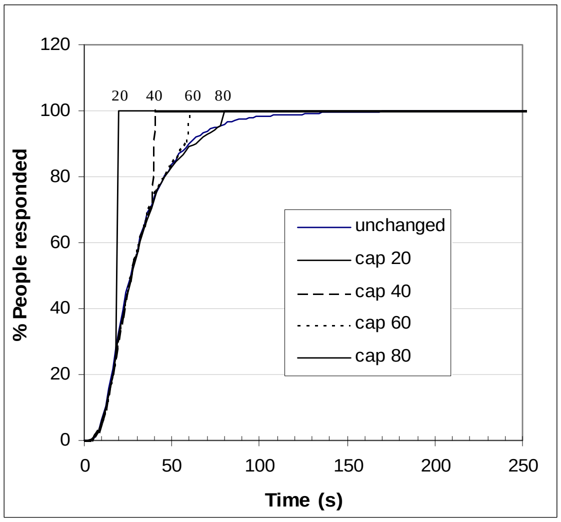



Fig. 7. Curtailed PTAT distributions due to occupants seeing the fire at various times

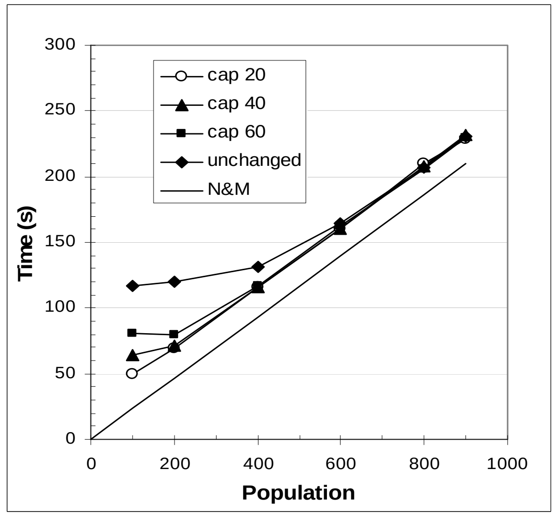



Fig. 8. Effect on 99% evacuation times



Another possibility is that the PTAT distribution may not be log-normal. In particular, the shape of the PTAT distribution might change if, after a certain time, the occupants saw the developing fire and then all decided to leave at once [6]. Figure 7 shows the PTAT distributions resulting if a sudden movement of all occupants occurred after 20,40,60 or 80 seconds, while Fig. 8 shows the effect on the 99th percentile evacuation times. The total evacuation time is not reduced until the occupant population is less than approximately 50% of the design population and only marginally for populations above 30% of the design population. Exit choice behaviour was idealised - all occupants dispersed evenly to their nearest exit. Equations 1 and 2 can be calculated assuming different numbers of people use different exits. With a sub-optimal exit choice the flow rate limitation of the exits becomes even more dominant.

For the crowded evacuation case it has been demonstrated that evacuation time depends upon the presentation time of the first few occupants, followed by the exit flow time. In order to examine the sensitivity of the evacuation time outcomes to the presentation time figure, a series of runs was carried out using different single presentation times, compared with the evacuation time computed using the detailed simulation. The results are shown in Fig. 9 for different assumed presentation time values from 0 to 30 seconds. The best fit with the actual full data is obtained by a presentation time of 17 seconds.

## Validation

The different elements of the GridFlow model with respect to aspects such as the relationship between occupant density and movement speed, default unimpeded movement speeds, maximum horizontal and vertical flow have been based upon those derived from experimental data and presented in Nelson and Mowrer [12], and the model has been validated to confirm that it delivers occupant movement according to these variables. Overall performance has also been validated against an experimental single enclosure case, delivering similar evacuation times and patterns for a similar population. Details of the model performance and validation are presented in Bensilum and Purser [1].

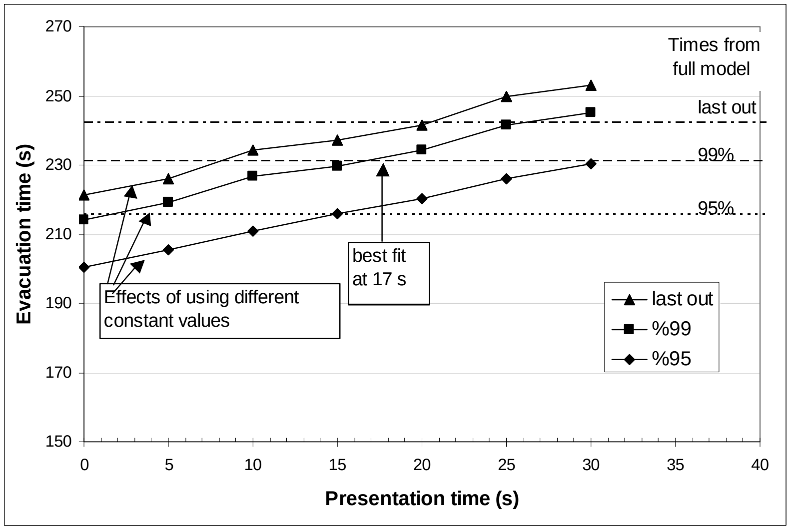



Fig. 9. Effect of using different constant values for 1st percentile presentation time on calculated evacuation times compared with results of the full simulation

**Results of multi-enclosure building evacuation simulations**

Having examined critical aspects of single enclosure evacuations, the next set of cases were used to examine the main drivers for multi-enclosure cases, especially multi-storey buildings. The purpose of these simulations was to identify and evaluate the effects of the main drivers of evacuation flow time from multi-enclosure, multi-storey office buildings containing design populations determined according to the UK prescriptive code (Approved Document B [13]) – i.e. crowded cases. Of particular interest were the effects of storey exit and stair widths, standing capacity on stairs between floors, and merge ratios (between occupants leaving floors and those descending a stair from the floor above), on minimum times to clear each floor into the protected stair. Maximum exit flow rates were set at 80 persons/metre/minute effective width (60 persons/metre/minute effective width for stairs). The storey exit and stair width provision of the codes is based upon a flow time of 2.5 minutes into the protected stairs, and (for simultaneous evacuation) that there is sufficient capacity (standing room) in the stair to accommodate the design population, less those evacuating from the final exit within 2.5 minutes [14-16]. A storey exit is discounted on the fire floor (blocked by the fire), so the entire population of one floor enters a stair at that level (half for other floors [for a two-stair building]) [13]. Cases include phased and simultaneous evacuation of code-compliant buildings with different numbers of floors and stair layouts (all representing "crowded" case, flow-limited, situations), with stair capacity set at 2 or 4 persons/m$^2$ standing room on stair treads and landings.

**Movement on stairs and merging behaviour in GridFlow**

Figure. 10. illustrates the stair layout as represented in the GridFlow simulations, and the flow and merge patterns observed. Although different stair geometries and layouts were examined, the default design was as shown, consisting of a half landing, two flights, and a storey exit landing with occupants entering from the lower left side. In the model, occupants descending from the floor above that illustrated are "transported" to the half landing above the storey exit via a link (marked by the thickened black line) from the half landing of the floor above, and descend the right hand flight to the storey exit landing where they turn through 180°, merging with occupants entering the stair via a link from the left. They then descend the flight to the half landing below, where there is a link to the half landing in the next lower stair element. Occupants descending the stair thus merge "naturally" in the simulation with occupants entering the stair via the storey exit. In the model, occupants descending the flight from the floor above tend to move towards the center handrail as they approach the storey exit landing, in order to take the shortest line to the flight descending to the next half landing, slowing somewhat as they make the 180° turn. This pattern of movement creates space for occupants entering through the storey exit to flow onto the landing, turning left and descending on the left hand side towards the mid-landing below. The overall result of these flow patterns is an almost exactly 50:50 merge ratio between the two streams of occupants. Fig 11 illustrates a GridFlow run paused in progress of a simultaneous evacuation on of a 10-stories served, 2-stair office case (for which half the building is modelled – involving one stair). The fire is on the ninth floor so that the number of occupants entering the stair at that level is doubled. The floors are represented on the left,

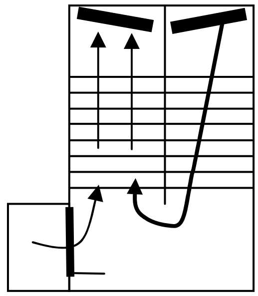


Fig. 10. Representation of a stair element in GridFlow

lobbies in the middle and stair elements on the right. Figure 11 illustrates a major consequence of the observed 50:50 merge ratio – that the floors clear from the bottom up, with the flow rate from the storey exit of each floor halving progressively on successively higher floors, once the stairs a full to capacity. The first floor clears first and the ninth floor last. The 10th floor clears quickly because there are no occupants descending from the roof. The simulation has been paused just after the first floor has cleared. The results of these simulations are illustrated in Fig. 12, which shows the time for evacuation into a protected stair for each floor of two-stair buildings, for 4-10 storeys served, designed for simultaneous evacuation according to Approved Document B, with a maximum density on the stair of 4 persons/$m^2$.

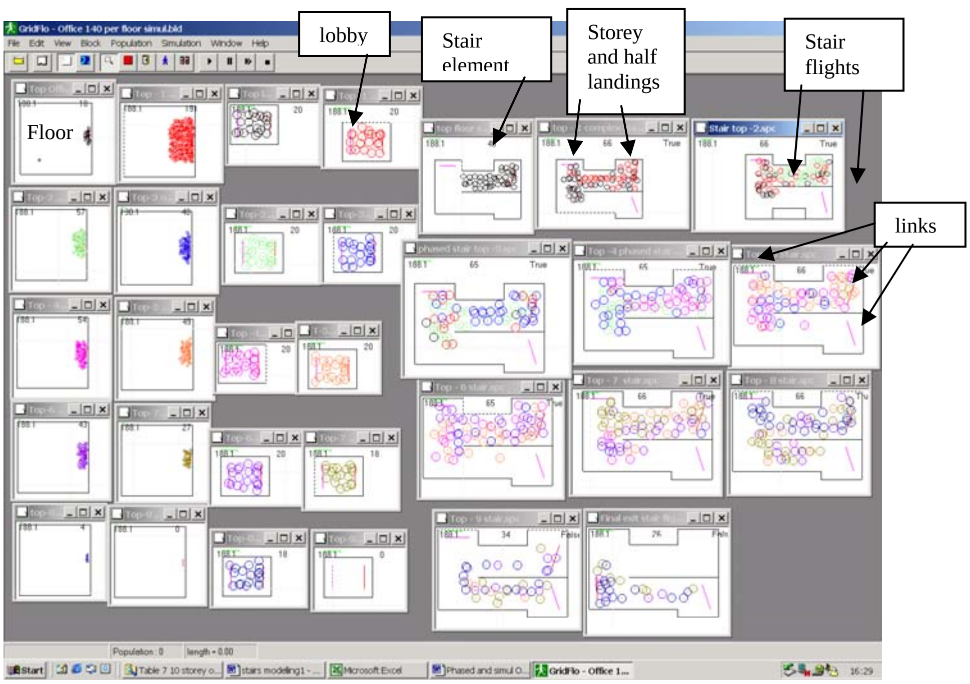
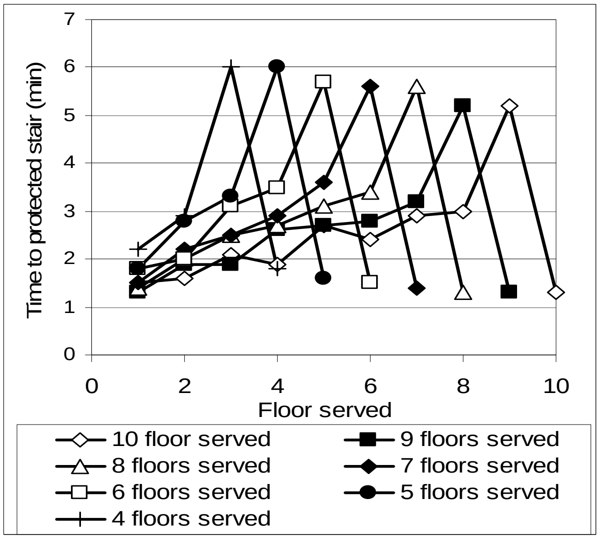



Fig. 11. Illustration of a GridFlow simulation of a simultaneous evacuation paused in progress

Assuming a density below 4 persons/$m^2$ had a significant effect on evacuation simulations as shown in Fig.13, which illustrates the effect of densities on the stair of 2 or 4 persons/$m^2$, for the 10- and 5-storeys served cases. A fire is assumed on the 9th or 4th floors so that the number entering the stair on those floors is doubled. In other experiments, simulations were carried out for which the merge ratio was adjusted to favour occupants already on the stair at the expense of those attempting to enter at the storey exit. This resulted in the opposite evacuation pattern whereby the upper floors cleared first.

Based upon this work it is concluded that, with simultaneous evacuation of several floors, the times required to clear each floor of a multi-storey building, and the patterns of floor clearance, are likely to depend upon the merge-ratios at the storey exits and the standing capacities on the stairs (which are in turn dependent upon the densities taken up by occupants on the stairs during crowded evacuation conditions).



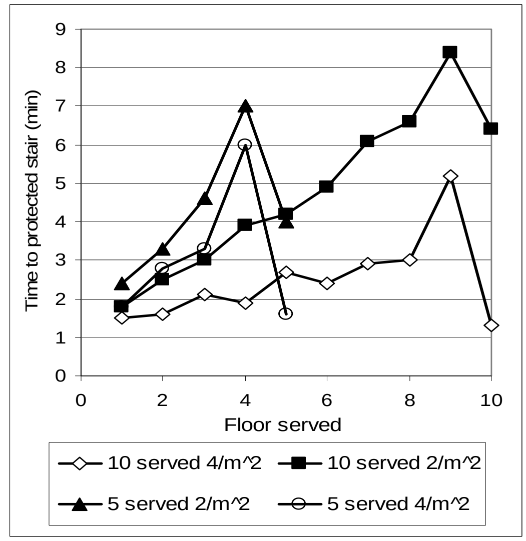




Fig. 12: Time for evacuation into a protected stair for two-stair buildings prescriptively designed for simultaneous evacuation: 4- 10 storeys served, 4 persons/m$^2$ maximum occupant density on stair

Fig. 13. 5 and 10 storeys served at maximum occupant densities on stair of 2 or 4 persons/m$^2$



**Validation**

Maximum flow rates through horizontal exits and down stairs in the GridFlow simulations were set to the relatively well established limits [12]. However, few data are available on the densities adopted by occupants evacuating buildings under crowded conditions, or merge ratios actually achieved at storey exits under crowded conditions. To obtain data on these, a series of monitored unannounced evacuations were carried out in four buildings with different stair layouts in London and in Ulster (by D.Purser and K.Boyce) [17]. The tests also presented an opportunity to validate published maximum exit and stair flow rates. The summarised findings are as follows:

- Horizontal exit and stair flow rates agreed quite well with the SFPE model at 86.7 p/min/m effective width (57.8 p/min/m full width) for exits and 60.1 p/min/m effective width (45.6 p/min/m full width) for stairs (stair widths 0.85-1.3 metres in different buildings), although under optimised "drill" conditions, higher rates were obtained at 99.4 p/min/m effective width (61.1 p/min/m full width) for exits and 72.9 p/min/m effective width (55.4 p/min/m full width) for 1.25 metre stairs [18].
- The maximum densities achieved during crowded evacuation conditions (sufficient to result in periods of no or very slow movement), were relatively low, with maximum densities for four buildings under near static flow conditions averaging 2.1 persons/m$^2$.
- For experiments in buildings with different stair layouts, although merge ratios sometimes favoured stair occupants and sometimes favoured storey exit occupants for short periods of 10-20 seconds, they almost always averaged close to a 50:50 merge ratio over longer periods (average for four building 50.6:49.4 stairs-storey exit), despite variations in stair layout expected to favour flow dominance either by the stair occupants or the occupants form the storey exit. Buildings were found to clear from the lower floors up, with the floor clearance rate halving at progressively higher floors
- Simulations of the experimental conditions resulted in similar outcomes to those obtained in practice. On this basis it is considered that the experimental evacuations validated the findings from the GridFlow simulations, confirming the flow rates, densities and merge ratios, and the effects on evacuation patterns obtained during the simulations. They also confirmed the importance of these variables in the determination of floor clearance times and patterns in multi-storey buildings.

**DISCUSSION**

Computer evacuation simulations are becoming increasingly sophisticated, but the details of these models cover mainly the movement phase of evacuations, as occupants flow towards exits and through evacuation routes, ignoring pre-travel aspects. Some models now include interactions with cues from the built environment influencing exit choice behaviour, while others have more detail on movement behaviour of large crowds [1-5]. These may improve simulations of reality, but in face of this increasing complexity it is maintained that a place exists for an alternative, simplifying, approach, by attempting to sort out key drivers of evacuation time from the detail of other aspects having only marginal effects on outcomes.

The benefits of simpler approaches, where demonstrated to be valid, are that they provide simple tools enabling a designer to experiment with different design concepts before committing to a detailed analysis, while identifying most features of a design likely to have a major effect on evacuation performance [6]. They are then complementary with later application of detailed simulations as the design matures, and provide useful tools for basic checking comparisons of computer simulation design cases. This may be particularly useful to ensure that a computer simulation has considered and adequately dealt with all the most important input variables likely to influence outcomes. The work presented was mainly carried out to investigate the performance outcomes of prescriptive design codes on generic buildings of different types.

The findings, which have been partially validated both against detailed computer simulations and experimental evacuations, are that both for single enclosures and multi-storey buildings, evacuation times and patterns can be quite well represented by a relatively small number of key variables.

For any specific enclosure, it is crucial that PTAT distributions are adequately represented. Based upon experimental findings from monitored evacuations of a number of buildings in different occupant categories [7], it is considered that PTAT is best represented by a variable period from alarm to that when the first few occupants begin to move towards the exits, followed by a log-normal distribution until the last few occupants move [1,9,10]. The time to, and width of, these distributions have been shown to have a profound effect on the total evacuation time of an enclosure or entire building, yet in engineering calculations and computer evacuation simulations, PTAT is often represented by a simple constant or "rectangular" time profile. Based upon the analysis performed, the most important aspects of the PTAT distribution are the times at which the few occupants begin to move (1st percentile) and that when the last few occupants begin to move ($99^{th}$ percentile). It these two times are known, the exact profile between may be less influential on evacuation times. Both crowded and sparsely occupied cases should be considered. The other main drivers for single enclosure (or entire building) evacuation times are exit choice behaviour, escape route widths and maximum specific flow rates through exits and on stairs. Although horizontal and vertical flow rates data are relatively well established (see review data [3,9]), there is some controversy over values that should be used for design purposes, and quite small differences in assumed maximum specific flow rates can have a significant influence on evacuation patterns and times. In this work, the maximum flow rates through storey exits, on stairs and through final exits during unannounced evacuations have mostly been found to be close to the SFPE values of 80 persons/min/metre effective width (horizontal) and 60 (stairs), although higher exit flows were observed under more regimented conditions, and during staged flow experiments [19]. On the other hand the default maximum flows, which were mostly measured some years ago, may now be too high to adequately represent the modern reality of more obese, infirm and aged building occupant profiles.

For multi-storey (or multi-enclosure) buildings, simple methods are useful for calculating total building evacuation times, but estimation of clearance times for individual floors is better performed using computer simulations. In experimental evacuations and GridFlow computer simulations, the time to clear each floor into the stairs for any specific exit and stair width was very dependent upon three parameters:

- horizontal and vertical flow rates – as discussed above
- "Standing" capacity of the stair between storeys – which for a given stair depends upon the horizontal area of the stair treads and landings and the assumed "packing" density taken up by the occupants as they descend the stair, and was found to be close to 2 persons/$m^2$.
- Merge ratio at storey exits between occupants on the stair and those from the floor, which was found to average around 50:50, irrespective of the stair layout (average for four building 50.6:49.4 stairs-storey exit), despite variations in stair layout expected to favour flow dominance either by the stair occupants or the occupants form the storey exit.

## CONCLUSION

From this work it is concluded that simple calculation methods can provide a useful first estimate of evacuation times for design purposes, and a useful check on the performance of more complex simulation models. It is also considered that evacuation times are very dependent upon a small number of critical factors (including PTAT distributions, exit choice ratios, maximum flow rates, merge ratios, and densities of stationary and moving groups), and that even the most sophisticated computer simulations can give misleading results if all these factors are not adequately represented.

**REFERENCES**


[1] Bensilum, M. and Purser, D.A., (2003). Grid Flow: An Object-oriented Building Evacuation Model Combining Pre-movement And Movement Behaviours For Performance-based Design. Fire Safety Science 7: 941-952. doi:10.3801/IAFSS.FSS.7-941

[2] Filippidis, L., Galea, E.R., Gwynne, S., Lawrence, P., Representing the Influence of Signage on Evacuation Behavior within an Evacuation Model. Journal of Fire Protection Engineering, 16 (1), 2006;pp.37–73. doi:10.1177/1042391506054298

[3] Thompson, P.A. and Marchant, E.W. A computer model for the evacuation of large building populations. Fire Safety Journal, 24: 131-148 (1995). doi:10.1016/0379-7112(95)00019-P

[4] Fraser-Mitchell, J.N. Lessons Learnt During the Development of CRISP2, a Monte-Carlo Simulation for Fire Risk Assessment. Interflam 1996, 7$^{th}$ Conference Proceedings pp. 631-639.

[5] Berrou, J.M, Beecham, J., Quaglia,P, Kagarlis, M.A. and Gerodimos, A. Calibration and validation of the Legion simulation model using empirical data. Pedestrian and Evacuation Dynamics Vienna. 2005.Proceedings Springer 2007.

[6] Purser, D.A., and Gwynne, S.V. Identifying critical evacuation factors and the application of egress models. Interflam 2007 11$^{th}$ conference. Proceedings pp.203-214.

[7] Purser, D.A. and Bensilum, M. Quantification of behaviour for engineering design standards and escape time calculations, Safety Science 38:157-182 (2001). doi:10.1016/S0925-7535(00)00066-7

[8] Purser, D.A., (2003). ASET And RSET: Addressing Some Issues In Relation To Occupant Behaviour And Tenability. Fire Safety Science 7: 91-102. doi:10.3801/IAFSS.FSS.7-91

[9] The application of fire safety engineering principles to fire safety design of buildings. PD7974-6: Human Factors: Life safety strategies - occupant evacuation, behaviour and condition. British Standards Institution 2004.

[10] Purser D.A. (2004) Structural fire engineering design: aspects of life safety. BRE Digest 490.

[11] Ashe, R. and Shields, T.J. Analysis and modeling of the unannounced evacuation of a large retail store. Fire and Materials 23, 333-336 (2000). doi:10.1002/(SICI)1099-1018(199911/12)23:6<333::AID-FAM707>3.0.CO;2-2

[12] Nelson, H.E. and Mowrer, F.W."Emergency Movement," *The SFPE Handbook of Fire Protection Engineering (3rd ed)*, DiNenno P.J. (ed) National Fire Protection Association, Quincy,MA,2002, pp.3/367-380.

[13] The Building Regulations 2000: Approved Document B Fire Safety 2007 Edition.

[14] Ministry of Works. Fire grading of buildings. Part II Fire detection and fire fighting equipment in buildings. Part III Precautions relating to personal Safety. Part IV. Chimneys, flues and hearths. Post-War Building Studies No.29. London, HMSO 1952. Reprinted by the Building Research Establishment 1992 , available from Construction Research Communications Ltd. London, 1992

[15] Fire precautions in the design, construction and use of buildings. Part 3. Code of Practice for Office Buildings. BS5588: Part 3, 1983. British Standards Institution.

[16] Fire precautions in the design, construction and use of buildings. Part 11. Code of Practice for shops, offices, industrial, storage and other similar buildings. BS5588: Part 11, 1997. British Standards Institution.

[17] Purser, D.A. and Boyce, K.E. “Relationship between stair width and evacuation requirements for workplaces and public buildings: D15 Report on results of stair flow experiments”. BRE Report 213270 9$^{th}$ March 2006

[18] Relationship between stair width and evacuation requirements for workplaces and public buildings D15 (V2) – Report on results of stair flow experiments. BRE Report 213270 9th March 2006.

[19] Seyfried, A.*et al.*Capacity estimation for emergency exits and bottlenecks. Interflam 2007 11$^{th}$ conference. Proceedings pp.247-258.