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INVESTIGATING THE IMPACT OF OCCUPANT RESPONSE TIME ON COMPUTER SIMULATIONS OF THE WTC NORTH TOWER EVACUATION

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ABSTRACT

This work explores the impact of response time distributions on high-rise building evacuation. The analysis utilises response times extracted from printed accounts and interviews of evacuees from the WTC North Tower evacuation of 11 September 2001. Evacuation simulations produced using these "real" response time distributions are compared with simulations produced using instant and engineering response time distributions. Results suggest that while typical engineering approximations to the response time distribution may produce reasonable evacuation times for up to 90% of the building population, using this approach may underestimate total evacuation times by as much as 61%. These observations are applicable to situations involving large high-rise buildings in which travel times are generally expected to be greater than response times.

INTRODUCTION

The evacuation of the World Trade Centre (WTC) towers [1] is of fundamental importance to the future design of high-rise buildings. The attack on the WTC towers brought home to the world the importance of providing adequate and robust means of evacuation in high-rise buildings. In this paper we explore the impact of occupant response time on the evacuation of the North Tower of the World Trade Centre (WTC1). In an earlier study [2], the buildingEXODUS evacuation model [3,4] was used to investigate the evacuation of WTC1. This analysis made use of a generalised response time distribution based on data derived from a study of published accounts of WTC survivors [5,6]. NIST have also investigated certain aspects of the WTC investigation using a variety of evacuation modelling tools [1]. The simulations undertaken by NIST utilised an instant response time distribution and so did not accurately represent the initial movements and potentially the subsequent evacuation evolution. In a more recent paper [7], the authors returned to their earlier WTC1 simulations using more reliable data than was available at the time of the original analysis. This involved more accurate information relating to the building geometry, building population size and fire fighter performance capabilities. The paper explores several 'what-if' scenarios centred on the tragedy including what would have happened had the building been fully occupied at the time of the attack and what would have happened had a single staircase survived linking those above the impact zone with the ground. The paper also used the WTC evacuation scenario to explore generic issues associated with the practical limits of building size that can be expected to be efficiently evacuated using stairs alone. In this paper we return to the previous simulations of the evacuation of WTC1 using an improved set of occupant response.

THE EVENT

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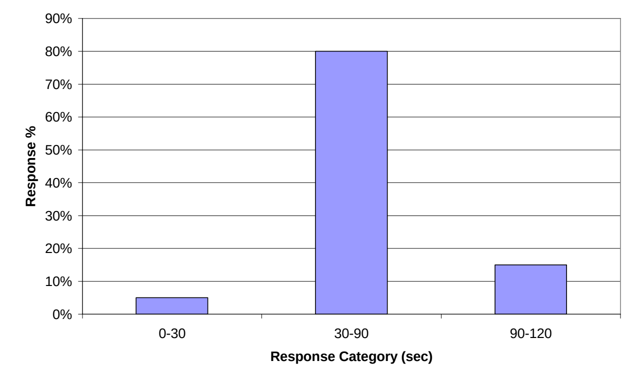
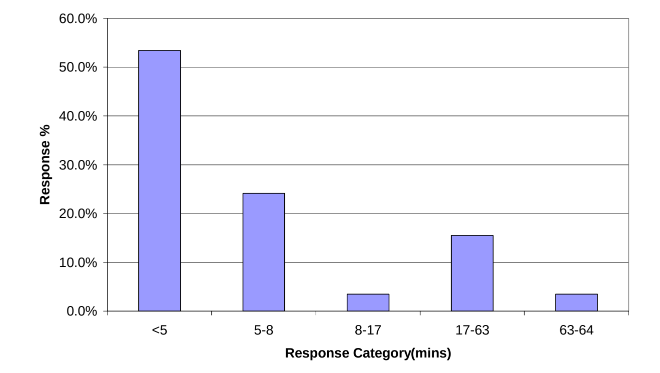
While the events of 11 September 2001 are well known, it is worth recounting the main facts. WTC1 was hit by American Airlines Flight 11 at 08:46 a.m. The impact was nearly centred on the north face of the building which was hit between the 94th and 98th floors. WTC2 was hit by United Airlines Flight 175 at 09:03 a.m. The impact was at a skewed angle toward the southeast corner of the south face of the building which was hit between the 78th and 84th floors. WTC2 collapsed at 09:59, 56 minutes 10 seconds after being hit and WTC1 collapsed at 10:28, 1 hour 42 minutes 5 seconds after being hit. There are various estimates for the number of people in the building and the number of fatalities. Denis Couchon of US newspaper ***USA Today*** estimates that there were between 5,000 and 7,000 people in the buildings at the time of the impact and estimates that 2,784 people perished [10]. NIST in their final report on the WTC evacuation [1] estimate that there were 17,400 +/- 1,180 people in the buildings (8,900+/-750 in WTC1 and 8540+/- 920 in WTC2). Couchon estimates that 1,432 building occupants perished in WTC1 and 599 in WTC2 [11], while NIST estimate that 1,462 and 630 building occupants in WTC1 and WTC2 respectively perished [1].

RESPONSE TIME DATA

Five response time distributions were investigated. This consisted of (a) instant response, (b) a skewed 0 – 2 minute response time distribution (see Figure 1a) referred to as Engineering Based, (c) a response time distribution based on data appearing in the public domain (see Figure 1b) [5,10], referred to as BDAG Based, (d) a distribution based on data derived from interviews with evacuees from WTC1 (see Figure 1c) referred to as Interview Based [8,9] and (e) a distribution based on a combination of the BDAG and Interview data (see Figure 1d). The Engineering Based response time distribution was arbitrarily defined as a skewed response time distribution that engineers would typically use in high-rise egress analysis. The BDAG data set consisted of 58 data points [5,10] while the Interview data set consisted of 78 data points.



(a) Engineering Response Time Distribution



(b) BDAG Response Time Distribution

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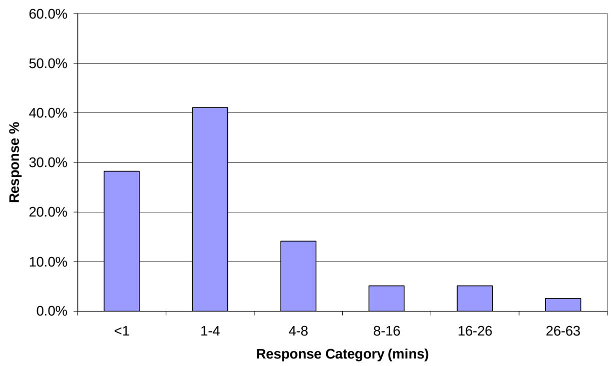
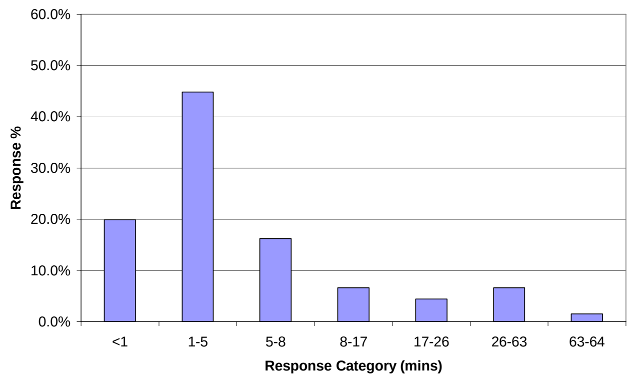


(c) Interview Response Time Distribution



(d) Combined BDAG and Interview Response Time Distribution

Figure 1: Response Time distributions used in analysis (note: bin sizes are not uniform)

At the time of writing the HEED team had not extracted response time data from the transcripts and so the response time data used in this paper was extracted by the authors from transcripts of interviews of evacuees from WTC1 [8,9]. While the HEED interview team conducted some 138 interviews of WTC1 survivors (see [8,9] for details) the authors were only able to determine a reliable estimate of the response time from 78 of the interviews. The Interview response time data was extracted from the transcripts in a similar manner to that employed in the BDAG analysis. The process used in this paper involved defining a total of 17 time sub-intervals around four known event times, namely the impact into WTC1 at 8:47am (**T1**), the impact into WTC2 at 9:03am (**T8**), the collapse of WTC2 at 9:59am (**T15**) and the collapse of WTC1 at 10:28am (**T21**) (see Figure 2). As an example of this process, consider the time span between T1 and T8. This was divided into six sub-intervals with **T4** being the sub-interval "Between T1 and T8" i.e. 08:47 < event time < 09:03, while sub-interval **T3** is "Closer to T1 than T8" i.e. 08:47 < event time < 08:55. The process of estimating a persons' response time involved reading the interview transcript and from the evidence provided suggest which time sub-interval best captured the response time of the evacuee. If the evacuee actually provided their own estimate of the response time this was used rather than the estimated time interval.

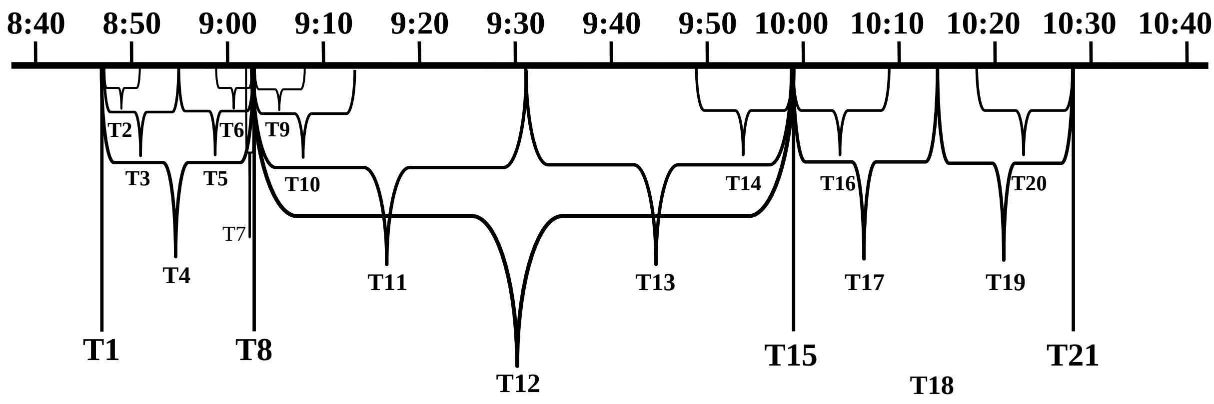


Figure 2: Time references used by the authors in the analysis of interview data

Where decisions could not be made due to insufficient information being available a time interval was not recorded and so no response time would be determined for that individual. Each time entry was determined by two analysts, any differences in interpretation were discussed and a final ruling made. In so far as it is possible, the team determined that there were no overlaps between the data derived from the BDAG and Interview analysis.

THE MODEL

The modelling of the evacuation of WTC1 was performed using the buildingEXODUS simulation software, developed by the Fire Safety Engineering Group at the University of Greenwich. The basis of the model has frequently been described in other publications [2-4] and so will not be described again here.

The Geometry

In attempting to simulate the events of 11 September 2001, the geometry of WTC1 was implemented within the software. The model assumes that there is no significant damage to the building below the impact zone and that the elevators are not available to assist in the evacuation. The geometry is considered to be a good representation of the actual building, being based on detailed architect plans [12, 13]. The broad structure of the building geometry represented within the software included the number and width of staircases, number of floors, number of unoccupied floors, layout of staircase geometry, widths of main doors, etc. However, given the complexity of the building, the geometry is kept as simple as possible while capturing all of the significant features. A total of 13 different floor plans were used to represent the key components of the WTC1 geometry. These were primarily intended to represent the change in the core layout, in particular the changing location of the staircase entry points due to the presence of transfer corridors. Details of the geometry can be found in [7].

The Population

Within the model the population was distributed only on the rented floors. So the floors known to have no tenants such as machine floors etc were left unoccupied. In the simulations presented here a population of 9,650 is used. This population is intended to represent the maximum number of people thought to have been in WTC1 at the time of the attack. This represents the population upper limit as estimated by NIST. From the NIST estimates it is thought that 1,462 people in WTC1 died, this included essentially everyone that was above the 91st floor (i.e. floors 92-110) and a few people on the lower levels [1], resulting in 8,188 survivors able to evacuate from WTC1. As complete and conclusive information concerning how these people were distributed throughout the building is not known, we assume that the population was distributed evenly amongst the remaining 77 floors producing an average number of 107 people per occupied floor and a total of 8,239 people within the entire simulation able to evacuate.

The gender distribution was set at 65% males and 35% females based on information from the media accounts [5,10] and also consistent with the NIST analysis [1]. The default maximum travel speed settings available within the software, which are functions of age and gender, were also adopted for these simulations. While it is known that some ten’s of people within WTC1 were mobility impaired, the simulations presented here do not attempt to represent these individuals. The default software age group settings (17-29, 30-50 and 51-80 years of age) were used. It was further decided that approximately 30% of the population would be in the youngest age group, approximately 50% in the middle age group and approximately 20% in the older age group. It is important to note that the modelled population does not represent the normal maximum working population of the building which is estimated to be 25,500 occupants and visitors [1]. Due to the relatively small building population used in these simulations, the staircases are not considered to be excessively loaded.

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The Scenarios

Five cases were investigated, one for each response time distribution. In each case software specific behavioural settings that were set included enabling the staircase packing parameter. This means that the stairs can be occupied to their full capacity if necessary. Finally, occupants on each floor were attracted to their closest entrance into the core region. From there they would select their nearest staircase entrance. As the software is a stochastic based simulation tool, it is necessary to repeat simulations a number of times in order to generate a distribution of results. For the main scenarios investigated in this paper, each case was repeated 50 times and average times are presented here. Each time the case was repeated the population would randomly change starting locations in such a way that the total number of people on each floor was not altered. The total evacuation times quoted in this paper are for occupants to exit the building.

Within the evacuation model, individuals are randomly assigned a response time based on the sub-interval their response time is assigned to. The frequency distributions shown in Figure 1 b,c and d represent the actual distribution used to produce the results presented in this paper.

RESULTS AND DISCUSSION

This scenario is an attempt to reproduce the primary events of the actual incident with the population size and distribution matching the best estimates available. This simulation involved 8,239 people who were able to evacuate the structure from the 91^{st} floor and below. These cases were executed using a 3.6 GHz Pentium 4 PC with 3.25 GB RAM. The run time for a single simulation was approximately 25 minutes.

The results for these simulations are summarised in Table 1 and Figure 3. The arrival curves for a representative simulation (with evacuation time close to the mean) for each of the cases is depicted in Figure 3. As can be seen from Figure 3 the arrival curves fall into two distinct types, those with short response times (scenarios 1a and 1b) and those with longer response times (scenarios 1c, 1d and 1e).

The cases with short response times are made up of the instant response time (scenario 1a) and a typical engineering response time distribution of up to two minutes (scenario 1b). We note from Table 1 that both these scenarios produce approximately the same average total evacuation times, with the engineering response time case producing an average evacuation time of 55 min 31 sec, some 2 min 27 sec longer than the instant response time case.

Table 1: Summary of results (average across 50 repeat simulations)

Response Time Distribution	Average Total Evacuation Time (8239)	90 % evacuated (7415)	98 % evacuated (8074)
1a Instant response time	0h 53m 04s	0h 43m 10s	0h 49m 47s
1b Engineering response times	0h 55m 31s	0h 45m 00s	0h 52m 02s
1c BDAG response times	1h 24m 33s	0h 55m 25s	1h 15m 40s
1d Interview response times	1h 20m 47s	0h 43m 54s	0h 50m 39s
1e BDAG+Interview response times	1h 25m 23s	0h 46m 25s	1h 12m 27s

The curves for these two cases are also similar suggesting that the evacuation dynamics for these cases are broadly similar (see Figure 3). The shape of the curves suggests that the evacuation takes place in three phases: an initial start up period, a central phase and final phase. The initial start up period is relatively short (0 – 200 seconds) and is a function of the time required for the early responders on the lowest floors to make their way out of the building, essentially unhindered by others. The central phase, which runs from 200 – 2,800 seconds, generates a relatively high egress rate, during which approximately 95% of the occupants have exited. In this phase all three stairs are working hard contributing to producing a constant building exit peak flow rate of 3.2 people/sec for scenario 1a and 3.0 people/sec for scenario 1b. This suggests that the stairs are producing approximately the maximum achievable flow. In the final phase (2,800 – 3,200 seconds) the egress rates diminishes as the number of people left in the building reduces and various stairs begin to dry up.

The 2 min 27 sec difference in total evacuation times between these two cases is essentially due to the 2 minute delay introduced by the response times. In this case, introducing up to a 2 minute response delay has little effect on the overall evacuation as the portion of the evacuation which dominates the flow dynamics is the stair descent. Introducing a phased start of up to 2 minutes therefore has little impact on the conditions on the stairs and the resulting overall evacuation time of approximately 50 minutes.

The cases with the long response times are made up of the BDAG response time (scenario 1c), the Interview response time (scenario 1d) and the combined BDAG+Interview response time (scenario 1e), the so-called “survey” cases. We note from Table 1 that all three of these scenarios produce similar average total evacuation times, with scenario 1c (BDAG) producing an average evacuation time of 1h 24m 33s and scenario 1d (Interview) producing an average evacuation time of 1h 20m 47s.

As with the previous two cases, the curves for the survey cases are similar suggesting that the evacuation dynamics for these cases are broadly similar. Furthermore, the shape of these curves (see Figure 3) once again suggests that the evacuation takes place in three distinct phases. As the survey cases release the majority of occupants within the first 8 minutes, the initial start up period is virtually identical to that of the other cases (0 – 200 seconds). Here again it is a function of the time required for the early responders (within the 0 - 8 minutes response time distribution) on the lowest floors to make their way out of the building, essentially unhindered by others.

The central phase where the maximum flows occur extends from 200 – 2,750 seconds. During this phase between 85% (BDAG) and 94% (Interview) of the occupants have exited. During the central phase, the survey cases are broadly similar to, but slightly slower than the rapid response cases. The similarity is due to the large number of occupants (approximately 80%) responding in less than 8 minutes in the survey cases. This results in much of the evacuation dynamics in this phase being broadly similar across all five cases. The final phase, which extends from 2,750 – 5,200 seconds, has a longer duration then in the rapid response cases. During the final phase, the flow rates decrease from their maximum values as the number of people remaining within the building drops to 15% for scenario 1c (BDAG) and 6% for scenario 1d (Interview) at the start of final phase. In addition to the small numbers of people remaining in the building during the final phase, the population is also dispersed throughout the building due to the spatial distribution of the longer response times leading to low population densities. This combination of relatively small numbers of widely dispersed people result in the marked reduction in observed flows and the extended nature of the third phase.

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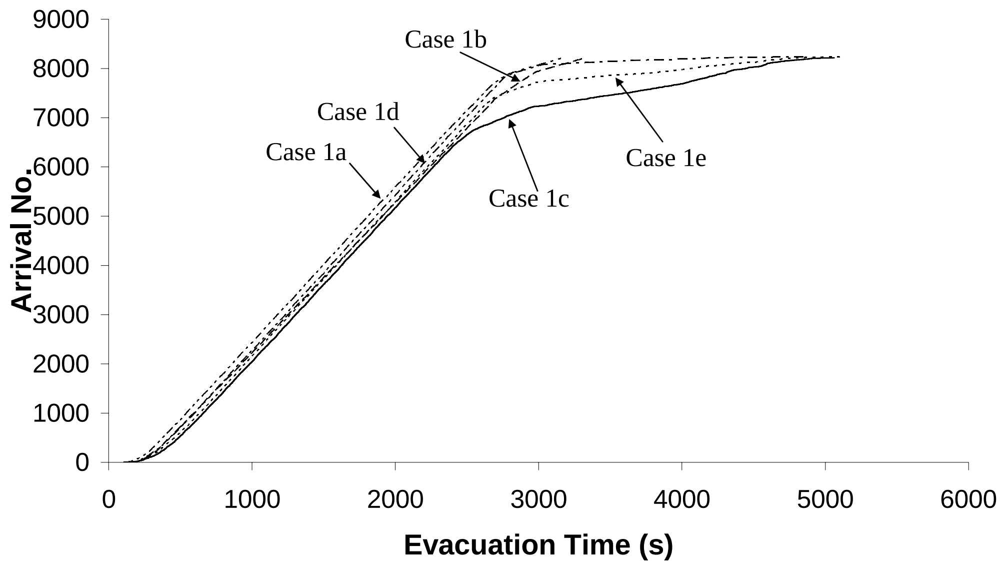

Figure 3: Comparison of arrival time curves for various response time distributions

While the survey cases produce broadly similar results, there are differences between these three cases. The Interview response time case (scenario 1d) produces shorter average evacuation times than the BDAG response time case (scenario 1c) as it has a greater proportion of the population reacting in under 8 minutes (approximately 93% compared with 78%). This results in the Interview case evacuating 98% of the population in approximately 51 minutes while the BDAG case requires approximately 1h 16m or 49% longer to evacuate the same number of people. In this respect, the Interview response time case (scenario 1d) is more similar to the instant (scenario 1a) and engineering (scenario 1b) cases, with all three cases evacuating 98% of the population in approximately the same amount of time, 51 minutes +/- 1 minute (see Table 1). This can also be seen in Figure 3 where the curves for scenarios 1a, b and c are almost identical up to approximately 51 minutes.

In addition, the BDAG response time distribution has a more significant tail, with 3.4% of the population responding in 63-64 minutes and 15.5% of the population responding in 17-63 minutes compared with the Interview response time distribution which has 2.6% of the population responding in 26-63 minutes. The larger number of people with long response times makes the average evacuation time for the BDAG case some 4 minutes (5%) longer on average than the Interview case. This relatively small difference in the total evacuation times for these two cases suggests that while the Interview distribution has only a small number of people with long response times, this small population is responsible for stretching out the total evacuation time in this case.

Combining the two survey based response time distributions produces the most realistic representation of the response time distribution for WTC1 as it utilises all the available data in a single distribution. In the combined distribution the relative number of people with long response times is reduced compared with the BDAG distribution but increased compared with the Interview distribution. The combined distribution produces a total average evacuation time of 1h 25m 23 s. This compares favorably with the estimated 1h 40m to evacuate WTC1. However, this is significantly different to the predicted evacuation time produced by the instant response case (scenario 1a) 53 m 04 s and the engineering response case (scenario 1b) 55m 31s.

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While the total evacuation time produced using the combined survey response time was some 61% longer (32 minutes) than in the instant response time case, the combined survey case produced similar predicted evacuation times and evacuation dynamics for up to 90% of the evacuating population (see Table 1 and Figure 3). Indeed, the time to evacuate 90% of the building population was only 4% longer when using an engineering response time distribution compared to an instant response time distribution and only 7% longer when using the combined survey response time distribution compared to the instant response time.

These results suggest that while engineering approximations to the response time distribution for evacuation simulations of high-rise buildings may produce a reasonable representation of the evacuation dynamics and evacuation times experienced by up to 90% of the building population, an accurate representation of the response time distribution is vital if realistic total evacuation times are to be predicted. If the actual response time distribution is likely to have a long tail, representing a small but non-negligible number of people with extended response times, as suggested by the survey response times used in these simulations, this will have a significant impact on the nature of the evacuation dynamics, especially in the final stages of the evacuation. Approximating the actual response time distribution using instant or arbitrarily short response time distributions will result in a poor representation of the final phases of the evacuation and potentially unrealistic estimations of likely total evacuation times. These observations are applicable to situations involving large high-rise buildings in which travel times are generally expected to be greater than response times.

CONCLUSIONS

This work has explored the impact of response time distributions on high-rise building evacuation. The analysis utilised "realistic" response times generated from the BDAG and Interview studies of evacuees from WTC1 and compared the evacuation times produced using these distributions with the estimated actual evacuation time of WTC1 and predicted evacuation times generated using instant and engineering response time distributions. Using the most realistic response time distribution based on the actual incident, the model predicts the total evacuation time for 8,239 evacuees – the maximum likely building population - to be approximately ***1 hour 25 minutes***. This time compares favourably with the estimated evacuation time of ***1 hour 40 minutes.***

More importantly, these simulations have highlighted the importance of using a representative response time distribution for high-rise building analysis. Approximating the actual response time distribution by an instant or arbitrarily short distribution may generate a reasonable approximation of the evacuation time for 90% of the building population. However, it is likely to fail to realistically represent the final phases of the evacuation, in particular the evacuation of long responders, thereby generating unrealistic estimations of likely total evacuation time. It is therefore essential to introduce a reasonable representation of likely tails into response time distributions used in engineering analyse of high-rise building evacuation.

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