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AN INVESTIGATION OF THE PROPORTIONALITY OF SAFETY MARGINS WITH INCREASED CEILING HEIGHT IN RELATION TO BS9999:2017

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ABSTRACT

Commonly, in both United Kingdom (UK) and international building regulatory guidance, a key factor used in escape route design is that of prescribed travel distances. These are maximum distances permitted for a building occupant to travel until they reach a place of safety, or a place of relative safety.

When fire occurs, due to the temperature difference between the products of combustion and the surrounding ambient air, buoyant smoke rises, tending to fill a volume from the ceiling down. Although the volumetric flow of a plume above a fire increases exponentially with height, an increase in ceiling height will nevertheless increase the time until escaping occupants are affected by the descending smoke layer. To the authors knowledge the only design document which explicitly takes cognisance of the advantage of increased ceiling height is BS 9999:2017 [1]. Designing in accordance with this document allows a trade-off between increased ceiling height and an increase in travel distance.

This paper examined variation in the margin of safety achieved for occupants escaping a simple one room office with a single means of escape, as the ceiling height is increased. The analysis compared the Required Safe Egress Time (RSET) with the Available Safe Egress Time (ASET) with varying ceiling heights, and travel distances proportioned according to BS9999:2017. Three scenarios were investigated which took into account variations in the assumed time before travel commenced.

It was concluded that the margin of safety afforded between ASET and RSET, increased with ceiling height. The increases in travel distance for this simple single room example were immaterial. This was attributed to queuing at the exit door dominating travel: the marginal increases in travel distance made no difference as the most remote occupants were travelling to join a queue to exit. It was further concluded that assumptions regarding the time prior to travel commencing were more influential than the marginal increases in travel distance with regard to the margin of safety, for the example examined.

INTRODUCTION

Commonly, in both United Kingdom (UK) [2][3][4][5] and international building regulatory guidance [6][7], a key factor used in escape route design is that of prescribed travel distances. These are maximum distances permitted for an occupant to travel until they reach a place of safety, or a place of relative safety. For example, this could be the distance from the remote corner of a room to an exit to the open air or a protected escape route. There are generally two travel distance limits specified: one for travel in a single direction, and a longer travel distance where there are two escape routes available. It is also permissible, with some caveats, that travel may be initially in a single direction leading to a point at which divergence to alternative escape routes is possible. The length of these permissible travel distances is dependent upon the building use, which in turn reflects the risk associated with different building types in terms of: fire hazard, occupant type, occupant familiarity and sleeping risk. In some respects, travel distance could be viewed as a proxy for travel time – for example where slower occupants are expected to be present, a shorter travel distance is required. This is to limit potential exposure to fire effluent.

Alternative approaches to Building Regulations Guidance using fire engineering include those proposed in BS 7974:2019 [8] and its associated published documents, or alternatively the International Fire Engineering Guidelines [9]. Whilst these methods contain a comprehensive systems approach, at their core lies a comparison of Available Safe Egress Time (ASET) with Required Safe Egress Time (RSET). Where ASET exceeds RSET, the intervening time represents a margin of safety. The concept of travel distance with this method is marginalised; if the occupants can safely evacuate the building prior to tenability limits being reached the distance they have to travel is not directly relevant.

An increase in ceiling height of a room or escape route increases the time until tenability is reached, all other factors being equal. The guidance to the UK building regulations does not take account of this advantage. It is worthy of note, that in the prescriptive guidance documents to the Building Regulations in the countries which make up the UK, a minimum escape route height, whilst unusual and unlikely, of 2m is permissible. To the authors knowledge the only document which explicitly takes account of the advantage of increased ceiling height is BS 9999:2017 [1]. Designing in accordance with this document allows a trade-off between increased ceiling height and an increase in travel distance, a decrease in door widths and a decrease in escape route widths, within specified limits.

AIM OF INVESTIGATION

This paper explores the correlation between increased ceiling height (and associated increases in time until tenability limits are reached) and the permissible increases in travel distance when designing in accordance with BS 9999:2017 [1]. By graphing ASET and RSET it was possible to compare how the margin of safety between the two varied as ceiling heights and travel distances increased proportionally.

MODELLING PARAMETERS

BS 9999:2017 [1] attributes the travel distances applied to a situation by 'Risk Profile'. This is based upon whether: the occupants are awake and familiar, or unfamiliar, if there is a sleeping risk, or if the occupants are receiving medical care. This is then linked to a likely fire growth rate, which relates heat release rate to time; this type of design fire is known as an αt^2 fire. For the case of an office it is assumed that the occupants are awake and familiar, and that the fire growth rate is 'medium' [1]. This leads to a Risk Profile of A2 if there are no enhancements to the minimum package of fire safety measures as specified in this British Standard.

Available Safe Egress Time (ASET) is the time from effective fire ignition until the time that the space is no longer considered as tenable for those escaping. There is no single universal tenability limit used in the Fire Engineering community, but rather whichever limit is first reached, or which limit is agreed as most appropriate in consultation with the Authority Having Jurisdiction. This may be for example the temperature of smoke at some predetermined height, or visibility through the smoke should occupants have to traverse an area where smoke has descended below head height. Often a height of

2.5m is used as a tenability criterion, linked with a maximum upper hot layer temperature of 200^{O} C [10]. This is representative of a safe level of heat flux received by occupants escaping below a hot layer of smoke. A hot layer of this temperature or above, descending below 2.5m would be unacceptable, however it may be calculated that a temperature lower than this could be tolerated where the upper hot layer height descends below 2.5m. For example, if occupants had to escape through smoke then a temperature less than 60° C may be tolerated for a up to half an hour.

The concept of Fractional Effective Dose (FED) may also be used when deciding upon a tenability limit. This can take into account heat, as the cumulative effects of convection and radiation, or a FED may be estimated for irritants and asphyxiant gases.

When visibility is considered, as well as the physical aspect of wayfinding, some design guides use this as a proxy for narcotic gases [11]. 10m visibility for large rooms is often a tenability limit [10].

Several different tenability limits could have been set for this investigation, however it was considered that only two tenability limits would be used for all scenarios. Consequently, it was decided that the visibility tenability limit would be set at 10m, at a 2m monitoring height and that the FED thermal for tenability was also not exceeded. As the results section show, in all cases visibility was exceeded earliest and so effectively there was a single dependent variable. The smoke descent was modelled using a simple zone model called B-Risk [12]. The default fuel in this software programme is polyurethane, which is considered conservative in terms of visibility. The fire was modelled as being on the floor; this produced the greatest height of rise of smoke to the ceiling and hence the greatest volumetric flow rate in the plume. Had the fire been raised off the floor, the temperature in the plume would have increased, but the volumetric flow would have been not as great. A sensitivity analysis was carried out for a fire at desk level (750mm) which confirmed that placing the fire at floor level produced more conservative results for visibility and FED thermal.

Required Safe Egress Time (RSET) is the time from ignition until evacuation is complete. This is made up of various stages: time to detection, time to alarm, pre-movement time, and travel time. In this paper the example used was a simple open plan room, which was relatively small. It is likely that a fire in such a space would be detected by the occupants before an automatic detector. In any event, the requirements in relation to this purpose group of building would be a manual fire alarm system. This would be designed in accordance with BS 5839-Part 1:2017 [13], which would require manual call points, rather than automatic smoke or heat detectors. It was assumed that the fire would be detected quickly by the occupants. Without automatic detection, suggested detection and alarm times are subjective. For the purposes of this study three RSET scenarios were adopted which incorporated notional detection times of 0,30 and 60 seconds respectively.

The time to alarm would depend upon either the occupant who discovered the fire alerting the other occupants vocally, or by activating a manual call point. Given the nature of the space, for the three RSET scenarios three notional times to alarm of 0,15 and 15 seconds were assumed.

Suggested pre-movement times for different management levels, building complexity and alarm systems are given in PD 7974-6:2019 [10]. However, these do not explicitly account for pre-movement in the room of fire origin. It may be expected that those in different parts of the building, not directly exposed to the fire may have longer pre-movement times than those in the room of fire origin. For an ordinary level of management, the pre-movement times are 1 minute for the first few people to start leaving (1st percentile) and a further 2 minutes for the last few people (99th percentile) to start moving towards an exit. However, it would also seem unrealistic that occupants in the room of fire origin would take as much as 3 minutes to start moving after a general alarm, particularly for an open plan office of relatively modest floor area. For the purposes of this investigation a different pre-movement time was adopted for each of the three scenarios, these were:

- A premovement time of zero for the 1st percentile and 30s for the 99th percentile in the first scenario.
- A pre-movement time of 30 seconds for the first 1st percentile and a further 60 seconds for the 99th percentile (90 seconds from Time to Alarm).
- A pre-movement times of 60 seconds for the first 1st percentile and a further 120 seconds for the 99th percentile (180 seconds from Time to Alarm), as per PD 7974-6:2019 [10].

The evacuation model used for this study is called Mass Motion [14] and was developed by Arup. A triangular distribution for the pre-movement times listed above was used.

The travel time is dependent on travel speeds and travel distance. The various travel distances shown in Table 1 were used; this was the only changing variable within the RSET calculation within each individual scenario. In order to ensure that the evacuation reflected this maximum travel distance, four occupants were positioned at the two room corners opposite the door; the remainder of the occupants were randomly spread across the rest of the floor. BS 9999:2017 [1] permits the reduction in escape route width with increased ceiling height, but a minimum door width of 850mm must be maintained where unassisted wheelchair access is necessary. Consequently, the door width in each of the evacuation models was kept as a constant 850mm.

One of the fundamental parameters of any evacuation is the number of occupants of the space. This number can be the number of people that the space is designed to hold, or alternatively the floor area divided by a floor space factor. BS 9999:2017[1] recognises different types of offices and offers three possible floor space factors: $4m^2$ per person, $6m^2$ per person or 10 m^2 per person. Examples of types of offices given are respectively: call centres, open plan offices or cellular offices.

The number of escape routes provided to a room or storey is limited within BS 9999:2017 [1] as a minimum of: one single exit for up to 60 occupants, two exits for 61-600 people and three exits for more than 600 occupants. As the example being analysed in this paper is a single room with a single exit, this limits the occupant numbers to a maximum of 60. Therefore, the floor area of the office could be taken as $240m^2$, $360m^2$ or $600m^2$ depending on which floor space factor is applied to a maximum of 60 occupants.

Table 1: Ceiling Heights and Travel Distances Incorporated in Models

Room Height (m)	Maximum Increase in Travel Distance with Ceiling Height (%)	Ceiling Heights used in Models (m)	Maximum Travel Distance used in Models (m)
≤ 3	Not Allowed	2.4	15
$> 3 \leq 4$	5	3.05	15.75
$> 4 \leq 5$	10	4.05	16.5
$> 5 \leq 6$	15	5.05	17.25
$> 6 \leq 7$	18	6.05	17.7
$> 7 \leq 8$	21	7.05	18.15
$> 8 \leq 9$	24	8.05	18.6
$> 9 \leq 10$	27	9.05	19.05
> 10	30	10.05	19.5

BS 9999:2017 [1] provides 'direct' and 'actual' travel distances depending on whether the final room layout is known. In the example analysed in this paper the shorter 'direct' travel distance was adopted as the layout was unknown. The extension in travel distance permitted by BS 9999:2017 in relation to the room height and the room heights modelled are summarised in Table 1 on the previous page.

The independent variables which changed between computer models were the travel distances in the evacuation models for the three RSET Scenarios, and the ceiling height in the fire model. The ceiling heights were taken from Table 14 of BS 9999:2017 [1]. The smallest room height of 2.4 m was chosen as this reflects a common construction dimension related to construction material sizes.

With regards to achieving the travel distances, it was necessary to adjust the aspect ratio of the room to vary between the minimum travel distance of 15m and the maximum travel distance of 19.5m, whilst keeping the floor area constant. Initially it was assumed that the floor area of the room used in the models would be one of the three mentioned previously, which would directly relate to the occupant capacity. However, it was found that for a rectangular room with a single exit in the middle of one wall (as shown in Figure 1) that the minimum travel distance could not be achieved in rooms with any of the room floor areas based upon an occupant capacity of 60 and the floor space factors from the British Standard. This may not be the case for other room geometries.

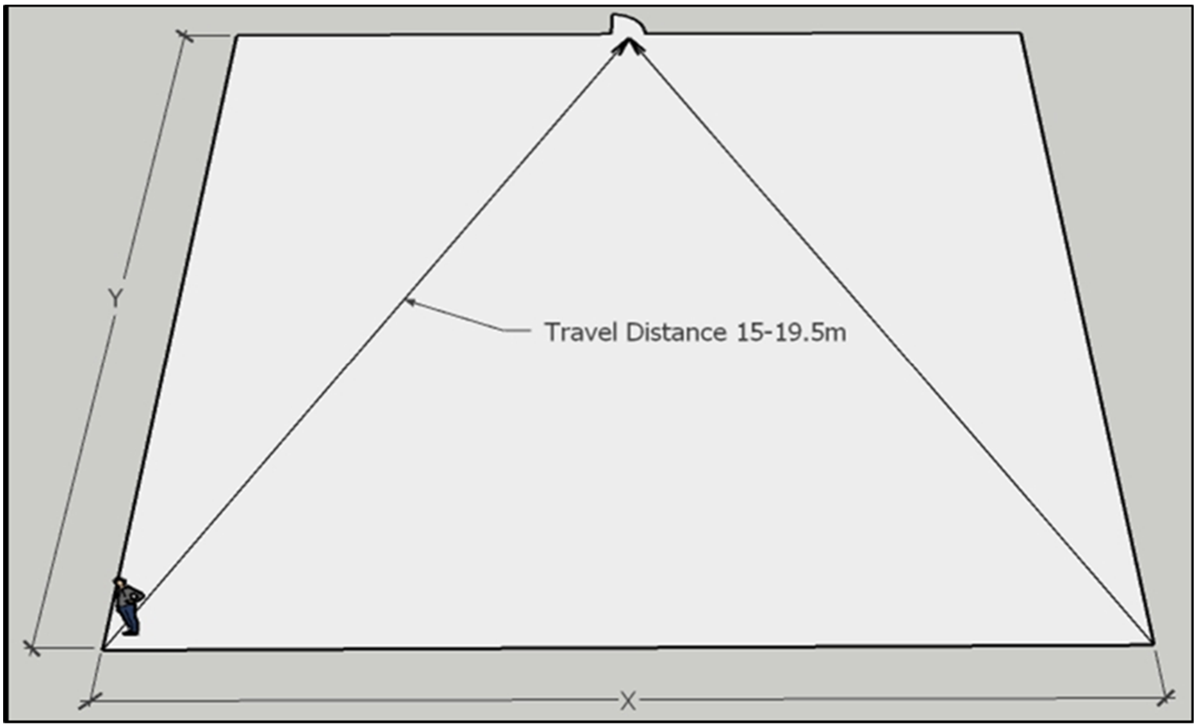

Figure 1: Sketch Floor Plan (NTS)

With reference to Figure 1, it may be seen that the depth of the room is given by:

$$Y = f(x) = Floor\ Area/X \qquad [1]$$

The shortest travel distance from Table 1 is given by:

$$15 = \sqrt{Y^2 + (0.5X)^2} \qquad [2]$$

$$\rightarrow 15^2 = Y^2 + (0.5X)^2$$

$$\rightarrow Y = f(x) = \sqrt{15^2 - (0.5X)^2}$$

The longest travel distance from Table 1 is given by:

$$19.5 = \sqrt{Y^2 + (0.5X)^2} \qquad [3]$$

$$\rightarrow 19.5^2 = Y^2 + (0.5X)^2$$

$$\rightarrow Y = f(x) = \sqrt{19.5^2 - (0.5X)^2}$$

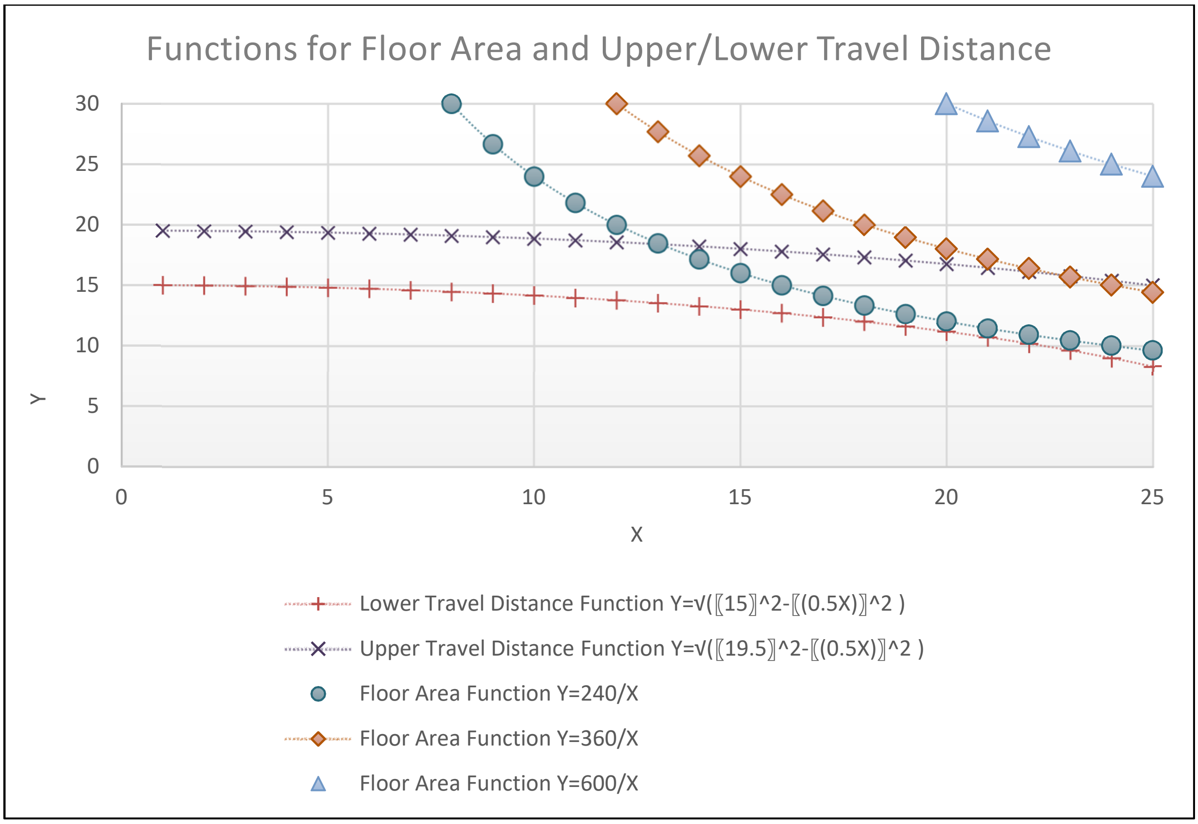

Figure 2: Functions for Floor Areas and Upper/Lower Travel Distances.

The graph in Figure 2 on the previous page shows the 15m and 19.5m travel distance functions and the graphs for the 240, 360 and 600m^2 floor area functions. Although the function for the 240m^2 floor area approaches the minimum travel distance function, they do not actually intersect. Therefore, there is a disconnect between the single escape, maximum occupancy, floor space factors and travel distances for a single office. The extended travel distance functions which do intersect the floor area functions would require a single exit. The ones which do not intersect would require two exits, or a reduction in the floor area and hence an occupant capacity of less than 60.

Table 2: Room Dimensions

Maximum Travel Distance used in Models (m)	**Travel Distance Function**	**Room Floor Area Dimensions**		
		Room Width X (m)	Room Depth Y (m)	Room Area XY (m^2)
15	Y= f(x)=$\sqrt{15^2-(0.5X)^2}$	21	10.71	224.91
15.75	Y=f(x)=$\sqrt{15.75^2-(0.5X)^2}$	16.94	13.28	224.96
16.5	Y=f(x)=$\sqrt{16.5^2-(0.5X)^2}$	15.41	14.59	224.83
17.25	Y=f(x)=$\sqrt{17.25^2-(0.5X)^2}$	14.33	15.69	224.84
17.7	Y=f(x)=$\sqrt{17.7^2-(0.5X)^2}$	13.8	16.3	224.94
18.15	Y=f(x)=$\sqrt{18.15^2-(0.5X)^2}$	13.35	16.85	224.95
18.6	Y=f(x)=$\sqrt{18.6^2-(0.5X)^2}$	12.89	17.45	224.93
19.05	Y=f(x)=$\sqrt{19.05^2-(0.5X)^2}$	12.49	18	224.82
19.5	Y=f(x)=$\sqrt{19.5^2-(0.5X)^2}$	12.14	18.53	224.95

In order to avoid providing a further exit (which would be less conservative), the floor area and hence the occupant capacity was reduced for the models analysed. Following an iterative procedure and setting Y initially as a whole number, in order that the function of the shortest travel distance be intersected by a floor area function, the X co-ordinate (room width) would be 21m and the Y co-ordinate (room depth) 10.71m, resulting in a floor area of 224.91m^2. The dimensions calculated for the intersection points for all the travel distance functions are included in Table 2 above and indicated in Figure 3 overleaf, for a room floor area function of Y=f(x)=224.91/X. The slight discrepancies in floor area in the final column of Table 2 are rounding errors. Using the minimum floor space factor for offices as 4m^2/ person, this would result in the number of occupants of the room being 56, rather than 60.

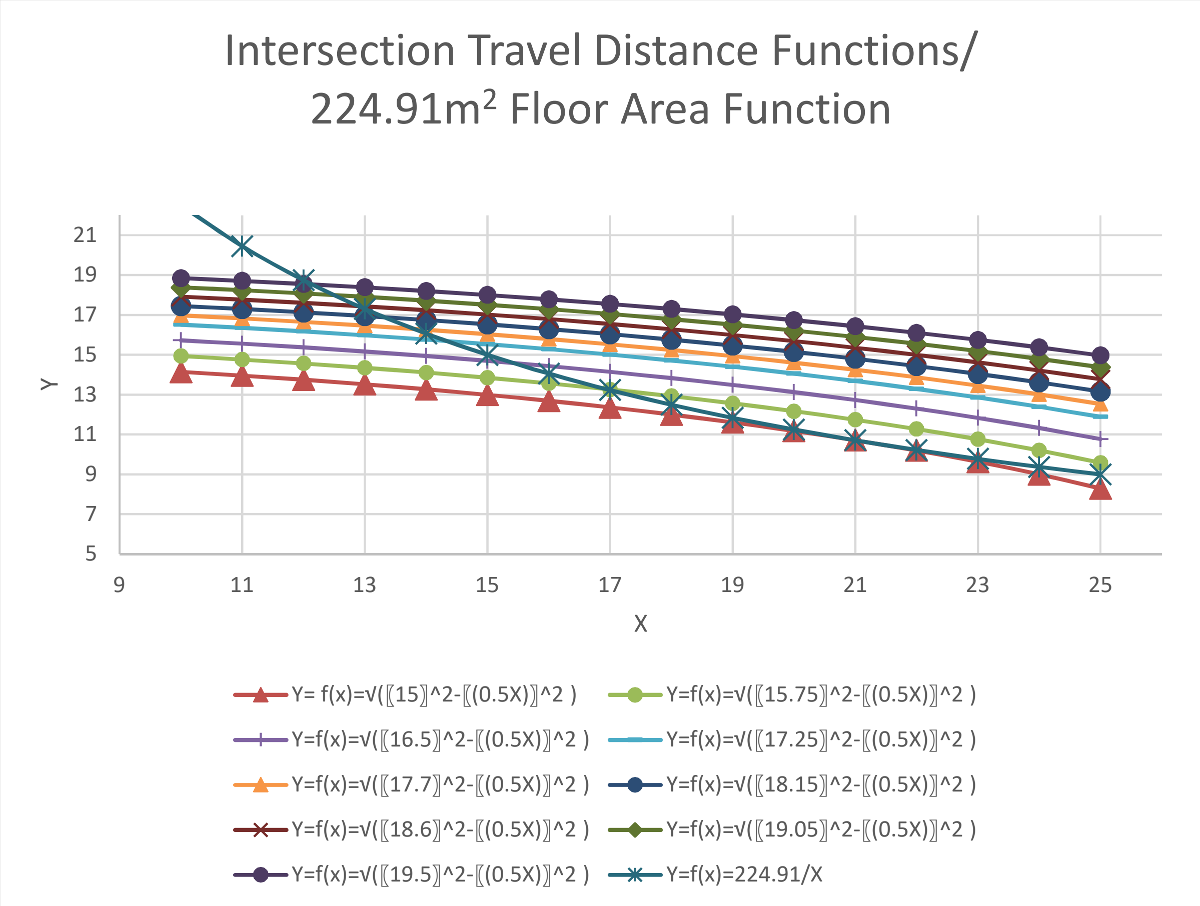

Figure 3: Travel Distance and Floor Area Functions

RESULTS

Table 3 provides details of the ASET from the zone models with varying ceiling heights. Tables 4-6 provide details of the RSET with varying travel distances for the three scenarios previously described. Figure 4 graphically represents the difference between the ASET and RSET at different ceiling heights.

Table 3: ASET Tenability Limit Times for Visibility and FED Thermal

Ceiling Heights (m)	**Associated Travel Distance (m)**	**Visibility Tenability Limit Reached (s)**	**FED Thermal Tenability Limit Reached (s)**
2.4	15	110	302
3.05	15.75	162	322
4.05	16.5	200	349
5.05	17.25	224	376
6.05	17.7	239	407
7.05	18.15	251	426
8.05	18.6	260	442
9.05	19.05	267	459
10.05	19.5	273	475

Table 4: RSET Scenario 1

Ceiling Heights (m)	**Associated Travel Distance (m)**	**Time to Detection (s)**	**Time to Alarm (s)**	**1st Percentile Pre-movement Time**	**99th Percentile Pre-movement time (from Time to Alarm)**	**Pre-movement and Travel Time Combined for Last Occupant (s)**	**RSET (s)**
2.4	15	0	0	0	30	66	66
3.05	15.75	0	0	0	30	65	65
4.05	16.5	0	0	0	30	64	64
5.05	17.25	0	0	0	30	64	64
6.05	17.7	0	0	0	30	63	63
7.05	18.15	0	0	0	30	65	65
8.05	18.6	0	0	0	30	68	68
9.05	19.05	0	0	0	30	65	65
10.05	19.5	0	0	0	30	66	66

Table 5: RSET Scenario 2

Ceiling Heights (m)	**Associated Travel Distance (m)**	**Time to Detection (s)**	**Time to Alarm (s)**	**1st Percentile Pre-movement Time**	**99th Percentile Pre-movement time (from Time to Alarm)**	**Pre-movement and Travel Time Combined for Last Occupant (s)**	**RSET (s)**
2.4	15	30	15	30	90	108	153
3.05	15.75	30	15	30	90	107	152
4.05	16.5	30	15	30	90	106	151
5.05	17.25	30	15	30	90	110	155
6.05	17.7	30	15	30	90	106	151
7.05	18.15	30	15	30	90	110	155
8.05	18.6	30	15	30	90	108	153
9.05	19.05	30	15	30	90	108	153
10.05	19.5	30	15	30	90	111	156

Table 6: RSET Scenario 3

Ceiling Heights (m)	Associated Travel Distance (m)	Time to Detection (s)	Time to Alarm (s)	1st Percentile Pre-movement Time	99th Percentile Pre-movement time (from Time to Alarm)	Pre-movement and Travel Time Combined For Last Occupant (s)	RSET (s)
2.4	15	60	15	60	180	183	258
3.05	15.75	60	15	60	180	185	260
4.05	16.5	60	15	60	180	175	250
5.05	17.25	60	15	60	180	183	258
6.05	17.7	60	15	60	180	178	253
7.05	18.15	60	15	60	180	175	250
8.05	18.6	60	15	60	180	182	257
9.05	19.05	60	15	60	180	186	261
10.05	19.5	60	15	60	180	182	257

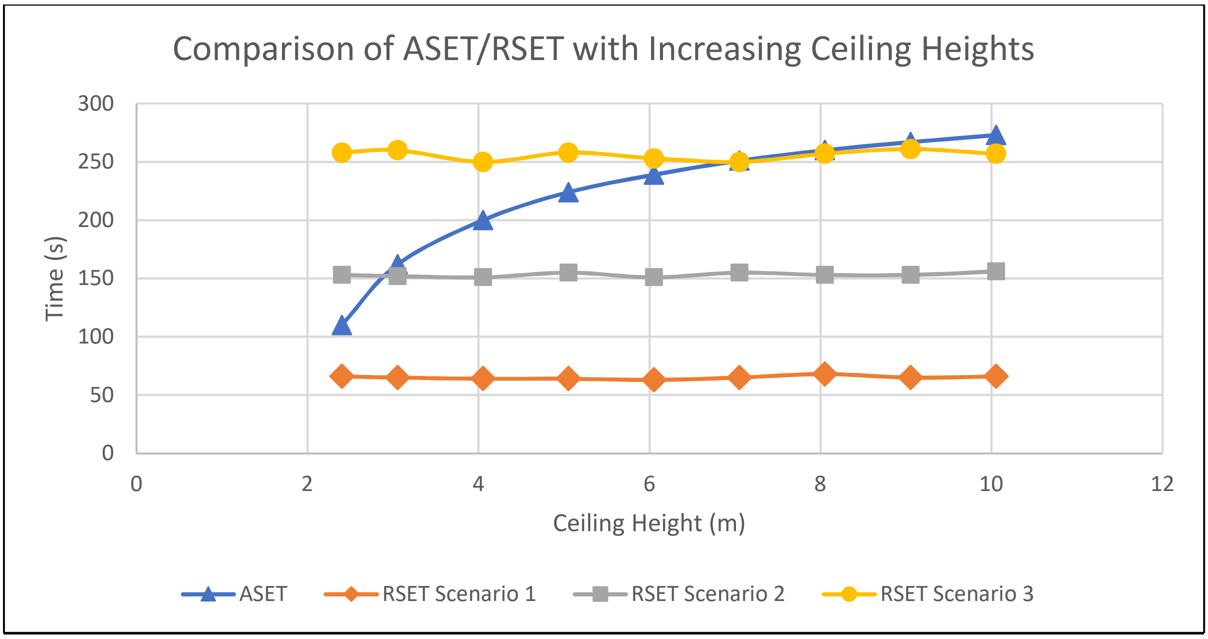

Figure 4: Comparison of ASET and RSET

CONCLUSIONS

When embarking upon this analysis, it had been assumed that there was a mathematical interconnection between floor space factors, maximum occupancy, travel distance and exit numbers. However, for this simple geometric shape, this was found not to be the case. As Building Regulation guidance has evolved in a piecemeal fashion over many years, and BS9999:2017 [1] is closely related to the Building Regulation Guidance, perhaps this should not have been surprising.

The RSET value from the computer evacuation model remained fairly constant irrespective of travel distance increase within each scenario. It is posited that there are three factors contributing to this:

- As the room layout was unknown the shortest travel distance for 'direct' was used. Consequently, the increase in travel distance would be proportionately smaller than had a longer initial travel distance been adopted. The maximum increase being 4.5m – with an unobstructed walking speed this would only take approximately four seconds to cover.
- It was noted that there was queuing to exit at the door and consequently the remote occupants were traveling to join the rear of a queue rather than directly exiting. Therefore, flow through the exit door was the determining factor rather than travel distance.
- As a movement distribution was being used, which randomly attributes start times, it was not necessarily those farthest from the exit who moved first. On occasion those agents overtook other agents closer to the exit door who had yet to start moving.

The graph in Figure 4 shows that ASET increases as ceiling height increases. The factor of safety between ASET and RSET is dependent on the pre-travel time assumed in each of the three scenarios. Where a very short pre-travel time was assumed in Scenario 1, there was always a margin of safety between ASET and RSET, which increased with ceiling height. With a more conservative pre-travel time in Scenario 2 there is no margin of safety below a ceiling height of circa 3m. With the most conservative pre-travel time in Scenario 3, there is no margin of safety until the ceiling height is approximately 7m, however as previously mentioned this RSET scenario does seem unlikely in the room of fire origin with these proportions.

These results suggest that travel distances greater than recommended in BS 9999:2017 may be possible without compromising the margin of safety for rooms with larger ceiling heights. For ceiling heights of 3.05m and less an inadequate margin of safety would not be resolved by reducing travel distance. As already discussed the RSET is governed by flow through the exit door. It should be noted that wider exit doors would increase flow.

LIMITATIONS

This analysis was carried out on a very simple one room layout of one occupancy type and incorporated a number of assumptions. There may be other geometries which exhibit different attributes than were used here. Also, the flow through the exit door is assumed to be unimpeded beyond, if this led to a corridor, then this may not necessarily be the case and RSET could increase.

The time to detection and time to alarm were assumptions which are subjective. If an automatic fire and smoke detection system were installed more certainty could be attributed to these factors. The pre-movement time and distribution was also assumed and are subjective. There is a paucity of data on pre-movement times in actual fires for the room of fire origin.

FUTURE WORK

BS 9999:2017[1] is a comprehensive document. It would be of interest to extend this research to: other building uses, varying occupant numbers, and escape routes within different occupancies and varying fire growth rates. This analysis suggests that there is a variation in the margin of safety for the particular geometry analysed, if this were the case elsewhere there may be the scope for, for example widening escape routes where there are insufficient margins of safety or increasing travel distances where the margin of safety exceeds an agreed acceptable minimum.

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