



Questioning the linear relationship between doorway width and achievable flow rate

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ABSTRACT

This paper challenges the currently assumed linear relationship between doorway width and achievable flow. The current view is seen as a simplification that may lead to an overly optimistic view of the achievable flow rates. Analyzed data are presented in order to demonstrate the impact that the actual use of the doorway and its design can have upon the flow rate generated. These data are then supported by the use of numerical simulations to demonstrate the impact that this overestimation can have upon the design process. It is contended that the specific flow rate assumed for a doorway should take into consideration not only its width, but also the design of the doorway (i.e., the opening and closing mechanism) and how evacuees behave in response to it. The issues raised have implications for the governing codes/regulations, engineering guidance and on the development of future computational egress models.

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1. Introduction

Egress calculations are often used to assess the expected performance of a specific egress arrangement during an emergency. Traditionally, this has required the use of equations to predict the achievable flow and the overall evacuation times. These equations are formed from empirical data collected from a number of sources, primarily non-emergency in nature [1].

Given the nature of configurational design, certain components limit the overall flow rate which can be achieved during egress movement. Some building components may have high flow capacities, while others may restrict the flow through a reduction in the space available. This is particularly evident where large numbers of people are involved in the egress movement. The assumptions made regarding these limiting components are therefore critical to the overall evacuation times predicted.

The flow rate associated with exit points is usually derived from a number of key sources [2–6]. The doorway width available is often reduced based on an assumed boundary layer; the resultant usable width is termed the effective width [5]. However, the width lost is

independent of the overall width of the doorway [5]. The final specific flow rate produced is assumed to be a linear function of the effective width of the doorway and the flow rate derived from empirical data.

This paper suggests that the currently assumed linear relationship between doorway width and achievable flow is a simplification, which can lead to an overly optimistic view of achievable flow rates. Analyzed data are presented to demonstrate the impact that the actual use and the type of doorway can have upon the flow rate. These data are supported by the use of numerical simulations to demonstrate the impact this overestimation can have upon the design process.

This paper argues that the specific flow rate assumed for a doorway should take into consideration not only its width, but also its design (i.e. the opening mechanism) and how evacuees behave in response to it. The issues raised can have implications for governing codes/regulations, engineering guidance, and on the development of future computational egress models.

2. Recommended engineering approach

We will briefly describe the engineering approach presented in the Society of Fire Protection Engineers (SFPE) Handbook [1] and

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the assumptions on which it is based. This method is selected as it is the most widely applied engineering technique. As with all of the hydraulic approaches, they are sensitive to the flow rates assumed within the calculations. This is particularly the case when examining high-density situations where the overall evacuation time is dependent upon the congestion produced, as opposed to the distances traveled.

2.1. SFPE handbook

Nelson and Mowrer [1] derived a descriptive system of movement based on the work of Fruin [2], Predtechenskii and Milinskii [3], and Pauls [4,5]. At the time of the development of this approach, this research represented the most detailed and respected data available. Nelson and Mowrer's work is based upon the assumption that the speed of an individual is dependent upon the population density. In turn, the density of the population and the speed at which the population is traveling determine the flow rate. The hydraulic method adopted is based on the following assumptions: that the population evacuates simultaneously, providing a reservoir of people to ensure the assumed flow rates; occupant decision-making will not interrupt the flow produced; and the flow is not significantly influenced by the presence of the disabled, or the movement impaired, with the population traveling at uniform speeds.

This engineering approach is dependent on a number of key terms: population density (occupants/m² or occupants/ft²); velocity (m/s or ft/min); effective doorway width (m or ft); and specific flow rate (occupants/m/s or occupants/ft/min). These terms are employed to determine the time taken to reach particular components and then the time taken to move through a congested area.

The speed of movement, S , for an occupant density, D , between 0.54 and 3.8 occupants/m² (0.05 and 0.35 occupants/ft²) can be determined by the relationship

$$s = k - akD$$

where a and k are constants whose values vary according to the component and the units used. Speed is therefore linearly related to density, and this equation becomes

$$(m/s) S = 1.4 - 0.37D$$

$$(ft/min) S = 275 - 786.5D$$

The specific flow, F_s , can be determined through the following expression

$$F_s = SD = k(D - aD)^2$$

Fig. 1 shows a graphical relationship between F_s and D for the case of a doorway.

Finally, the calculated flow rate F_c (occ/s) is established by multiplying the specific flow by the effective width of the doorway, W_e :

$$F_c = F_s W_e$$

Based on the calculations above, the maximum value of specific flow rate which can be achieved for a doorway is 1.3 occupants/m of effective width/second (24.0 occupants/ft of effective width/min). These maximum values (see Table 1) are often used in engineering calculations as the default value given that congestion is assumed, especially where the evacuation is dominated by the population size and density, rather than the distances which have to be traversed. Even though the specific flow rate is different for various exit route elements, it should be emphasized that the engineering approach described does not differentiate among the achievable flow rates of several different components (e.g. door-

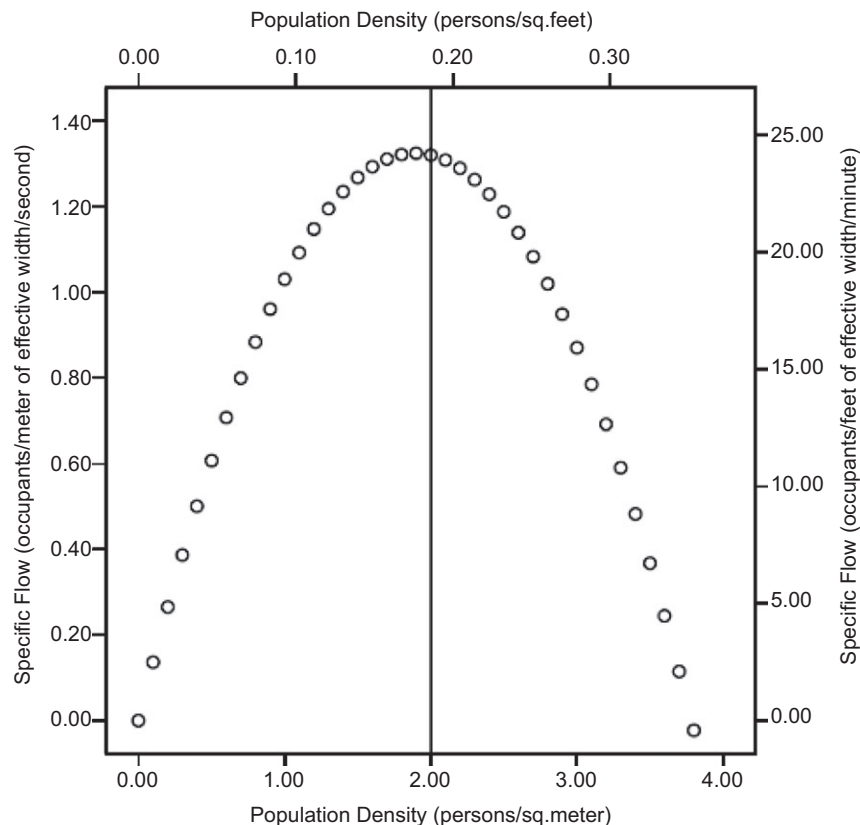


Fig. 1. Specific flow rate for the doorway/corridor/aisle/ramp as a function of density, redrawn from original [1].

Table 1
Maximum achievable specific flow rates [1]

Exit route element	Maximum specific flow rate	
	Occupants/ft of effective width/min	Occupants/m of effective width/s
Corridor, aisle, ramp, doorways	24.0	1.3
Stair (various configurations)	17.1–21.2	0.94–1.16

ways, corridors, aisles and ramps). In particular, it does not differentiate between different types of doorway mechanism. Critically, it does not differentiate between a simple narrowing of a corridor and the same narrowing with a door mechanism present, such as a free-swinging door leaf.

It is this maximum specific flow that is widely employed, and that will be referred to during the rest of this paper.

3. Discussion of data collection process

In order to examine the performance of people using exit doorways and to better understand the variables that may influence this performance, pedestrians were observed leaving a sporting arena. This footage was collected during the non-emergency use of these doorways. However, the footage included those periods of the day when the doorways would have been busiest, ensuring that congestion developed.

The cameras were positioned perpendicularly to the doorway plane. This allowed the camera to capture both the evacuee time of arrivals and the interaction of the pedestrians with the doorway as they moved through the door in question (see Fig. 2).

This original unpublished footage was shot by Fruin in 1989 [7]. The first step in the analysis was to digitize and lighten the images. The authors used the Adobe Premiere¹ movie editing software to re-format the footage and then to segregate the footage into discrete sections. This was required, as not all of the footage provided was usable. In some instances the use of the doorways became erratic or the view was obstructed. These periods were discounted, as a continuous supply of pedestrians was required to more reliably examine the flow rate through the doorways.

Where possible, the footage was separated into uniform time periods. Each section represented a 10-s period of the recorded footage. This enabled meaningful flow rates to be established. The 10-s period also ensured that no single individual would be counted in more than one section. During this period, the proportion of the doorway width available during any time period was established. This was formed from the door leaves being opened and closed during the movement of the population. This was established by comparing the current doorway width with the doorway width available, when the door leaf was fully opened (comparing Fig. 3(a) with 3(b)). In such a way, the percentage of the door space available could be established. This fluctuation in the available egress width is termed in this paper as *dynamic width*. This term, dynamic width, refers to the changing available width of the doorway, over time, due to its continual use. After a



Fig. 2. Sample snapshots of footage from the arena.

person passes through the door, the door may begin to close slightly (see Fig. 3(b)), leaving a smaller space for the next occupant to pass through. This phenomenon may have a non-linear impact on the achievable flow; not only because of the dynamic changes in the width available, but also because the remaining door width may only be wide enough for a single person, or may need to be opened wider to allow another individual to pass. It should also be recognized that the high volume of people using the doors in the data-set examined here should act to minimize the impact of the dynamic width; i.e. given that the doors should have less opportunity to close given the continuous flow of people.

The time periods analyzed from the video were selected so that there were enough people to ensure the doorways were fully utilized; i.e. continually being used given the buildup of congestion. This was based on the assumption that these rates could only have been produced if there was a sufficient supply of people to use the doorway.

4. Analysis of collected data

To generate the flow rates from our observed data, an estimate had to be made regarding the observed doorway widths. This estimate was produced on a number of bases: the typical door widths employed in the US; scaling from the width of smaller objects in the field of vision; and from observing the maximum number of people to use the doorway simultaneously and then cross-referencing this with anthropometric data [2,3,8]. Each of the doorways was estimated to be 36 in wide, producing a 72 in two leaf doorway from the arena.

The flow rates produced are presented in Table 2. By converting the flow rate into a specific flow rate and taking into account the effective width rather than the total width, the results could be compared with those values employed within the SFPE handbook. It is apparent that the flow rate produced falls below that assumed by the SFPE calculations; i.e. below that which would normally be applied in engineering calculations. The conditions were selected to ensure that the doorways were fully used, without producing excessive population densities that might lead to crush conditions or hinder the use of the doorways.

Given that the data relate to a set of double doors with no central separator, the effective width was applied to the entire door width; e.g. 12 in was subtracted from the entire width (72 in), producing an effective width of 60 in. Even if the effective width

¹ Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

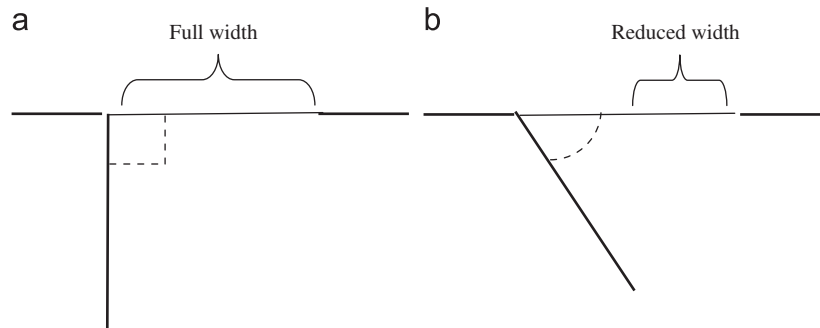


Fig. 3. (a) Doorway leaf is fully extended; (b) doorway leaf is less extended, obstructing some of the available doorway width.

Table 2

Flow rates collected from the arena

Observed component flow rate (occ/min) [min–max]	Observed specific flow rate-width (occ/m/s) (occ/ft/min)	Observed specific flow rate-eff. width (occ/m.eff.width/sec) (occ/ft.eff.width/min)	SFPE specific flow rate (occ/m eff. width/s) (occ/ft eff. width/min) [1]
84.5[60–126]	0.77(14.1)	0.92(16.9)	1.31(24)

reduction was applied to each door leaf (i.e., 24 in is subtracted rather than 12), then a specific flow rate of 21 occ/ft eff. width/min (1.15 occ/m eff. width/s) is produced; this is still below that used in the current engineering calculations.

These results are corroborated by the work conducted by Takeichi et al. [9]. Takeichi et al. [9] conducted a series of experiments in order to investigate the impact of merging flows. As part of this, a flow passed through a door in order to merge with another flow traversing a staircase. One of the variables examined was whether the door was open or closed. It was found that the status of the door had an important impact upon the results produced, with a 30% reduction in the flow rates produced through the door, when the door was initially closed, requiring the evacuees to interact with it as they passed through [9].

Fruin [7], in his earlier observations of movement in public spaces, collected data on the use of different types of doorway. He categorized the doorways examined according to the mechanism employed; e.g. revolving, free-swinging, turnstile, gate, etc. For free-swinging doorways, he observed flow rates ranging between 40–60 occupants/min (see Table 3). Interestingly, Fruin categorized these doorways according to type rather than according to width. He stated:

Entrances are, in effect, walkway sections in which pedestrians have been channelized into equal, door-width traffic lanes. In addition to imposing restricted lateral spacing in the traffic stream, entrances may require the pedestrian to perform some time consuming function such as opening a door or turnstile... Naturally, different entrance devices have different opening times, and each person will have varying degrees of skill in using these devices. The elderly, the physically handicapped, or those encumbered by packages or baggage will require longer door opening times [2].

In his analysis, the variation in the results was produced by the population densities at the doorway (there has been an attempt during this analysis to control this variable). Although we are not claiming that Fruin believed that the width of the doorway was

Table 3

Flow rates produced by Fruin according to doorway type [2]

Type of device	Equivalent pedestrian volume (occ/min)
Free swinging door	40–60
Revolving door	25–35
Free admission turnstile	40–60
Turnstile with ticket-collector	25–35
Coin-operated (low)-single slot turnstile	25–50
Double slot turnstile	15–25

unimportant, he did recognize the importance of the doorway design upon the flow rate, along with the population density at the doorway. His categorization of doorway types suggests flow rate is dependent on more than just the width.

The values provided by Fruin therefore relate to the flow rate produced by each doorway component (i.e. occ/time period) rather than according to the width of the doorway component (i.e. occ/unit width/time period). The doorway is treated as a single design component; i.e. the size of the leaf is less important than the fact that the doorway is of a leaf design. It is apparent that the observed flow rate from this unpublished 1989 data (presented here) falls within the specified range for a free-swinging door.

The data were examined to determine whether there were pedestrian behaviors which may have inhibited the flow rate produced. As the population was traversing the doorway, the visible doorway width was examined. The dynamic width of the doorway varied according to the interaction of the occupants and the distance they physically opened the door. In some instances the door leaves were fully extended (see Fig. 4(b)), while in others one or both of the leaves were partially closed, restricting the flow of the next person to travel through the door in each case (see Fig. 4(a)). In this data-set we are therefore examining the effect of the population's interaction with the door leaves.

From the data it is apparent that the dynamic width varied during the time periods examined. On average only 75% of the doorway width was available throughout the observed arena evacuation.

The variation produced during the time periods examined can be clearly seen in Fig. 5. The relationship between the number of people passing through the doorway leaves and the dynamic width is complex. The curves suggest that there is a correlation between the number of people who can exit and the dynamic width. However, time delays and other confounding variables would need to be examined to reach a statistically meaningful relationship.

Fig. 6 shows the specific flow rates produced based on different assumptions regarding the width available and the flow rates

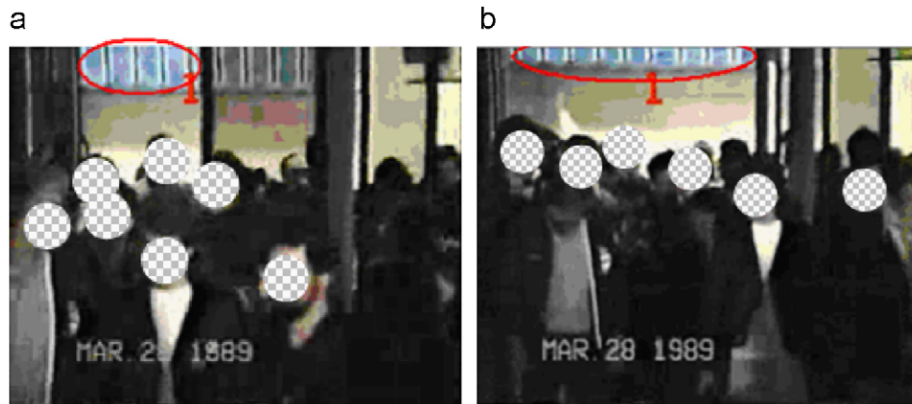


Fig. 4. (a) The doorway leaves are not fully extended, reducing the effective width; (b) the doorway leaves are fully extended.

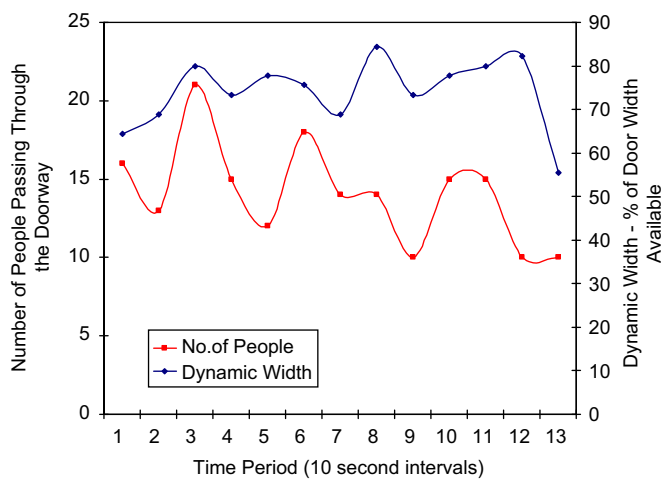


Fig. 5. The dynamic width produced during the time periods examined, in comparison with the number of people passing through the doorway at that time.

employed. The assumed engineering specific flow rate of 1.31 occ/m eff. width/s is shown as the horizontal dashed line. For the door examined this would provide a component flow rate of 2 occ/s (120 occ/min), which is over 40% higher than the observed rates.

The second curve was produced by dividing the number of people making use of the door in a time period by the effective width (1.52 m) of the door and by the time period (10 s). This only reaches the engineering rate of 1.31 occ/m eff. width/s during one time period with results ranging from 0.65 to 1.38, with an average 0.92 occ/m eff. width/s. *Therefore, assuming the availability of the effective width, a specific flow rate 30% less than the engineering rate is produced.*

The third curve was produced by dividing the number of people making use of the exit in a time period by the dynamic width (i.e. the remaining width given the position of the door leaves, see Fig. 5), the presence of an unused boundary layer, and by the time period (10 s).² In this case, the specific flow rate produced is closer to the assumed engineering flow rate (results ranging from 0.8 to 1.7, with an average of 1.25 occ/m dynamic width/s).

² This required the full physical width of the doorway (1.824 m) to first be reduced to the dynamic width; i.e. the physical space provided by the position of the door leaves. This then provided the physical width of the doorway during each time period. The effective width reduction was then applied to this width to be consistent with standard practice; i.e. a further reduction of 0.3 m.

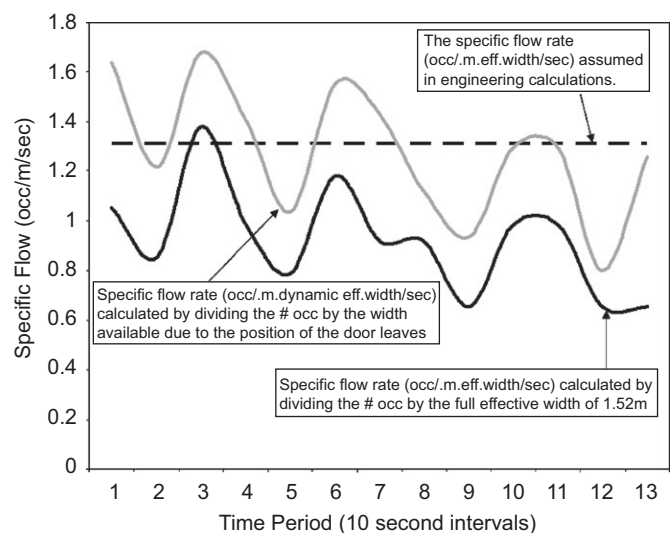


Fig. 6. The specific flow produced during the time periods examined.

From the observed flow rates, where doors are not mechanically held open, the flow rate will be reduced through interaction with the leaves and the width will be reduced below current expectation. To estimate the achievable component flow rates through doors that have closing door leaves, the following actions might be taken:

- A lower specific flow rate could be assumed for the effective width of the door; e.g. a value approximating the figure of 0.92 occ/m eff. width/s produced here.
- A reduced width should be assumed; i.e. the dynamic width of the exit be used to estimate the physical width, prior to the application of the effective width calculation.
- A component-based flow rate could be employed that is not sensitive to the size of the door leaf; e.g. the figure of 40–60 occ/min (0.66–1.0 occ/s) suggested by Fruin [2] in his original analysis.

Each of these remedial actions would consider the potential hindrance posed by door leaves that are not mechanically held open and produce more conservative component flow rates than would currently be the case. Assuming one of these actions is taken, the current engineering assumptions regarding doorway flow appear reasonable where doors are not mechanically held open.

The main result of this analysis is therefore that: (1) the interaction of the occupants with the door leaves delayed their progress; and (2) the variation in this interaction dynamically influenced the doorway width available, which in turn influenced the overall flow rates produced.

In the next section the potential consequences of employing the assumed and observed flow rates during egress calculations will be examined.

5. Demonstrating the potential impact on calculations

In this section, the impact of the discrepancies identified in the expected (SFPE) versus the collected flow rates is demonstrated. This will be achieved by employing a simple hypothetical scenario and then examining the egress performance (evacuation times) from it, using three different techniques: the model described in the Nelson and Mowrer chapter in the SFPE Handbook [1]; the EVACNET4 egress computational model [10,11]; and the buildingEXODUS computational egress model [12–15]. These two computer models were selected for two reasons: (1) they employ different movement calculations and represent the geometry and populations in entirely different ways; and (2) they are both able to impose flow rates upon the exit points within a structure.

The EVACNET4 model represents a geometry using a coarse grid where each structural component can be considered a single node. The nodes that form the structural network will likely be non-uniform. Each of these nodes can be simultaneously occupied by more than one person. The population is not represented individually, but in terms of the number of people who are within a node. The members of the population have no defining individual attributes. In contrast, the buildingEXODUS model represents a space through a mesh of $0.5\text{ m} \times 0.5\text{ m}$ nodes, each of which can be occupied by only one person at a time. The population is modeled on an individual basis. No judgment is made on the appropriateness of the two approaches adopted during this paper. However, the two models do represent significantly different approaches, both of which are widely used to make egress calculations.

The hypothetical case examined a single room that was occupied by 100 people who were assumed to respond immediately. These people exited via a single doorway, which was assumed to have an arbitrary effective width of 0.91 m (3 ft) (see Fig. 7). This configuration was employed by each of the three methods; however, each of the methods represents the space in different ways and requires different assumptions to be made. For each of the methods used, the observed flow rate was applied (0.92 occ/m eff. width/s from Table 2) in addition to the expected flow rate recommended in the Handbook (1.31 occ/m/s). Given the dimensions of the room, the population density produced is

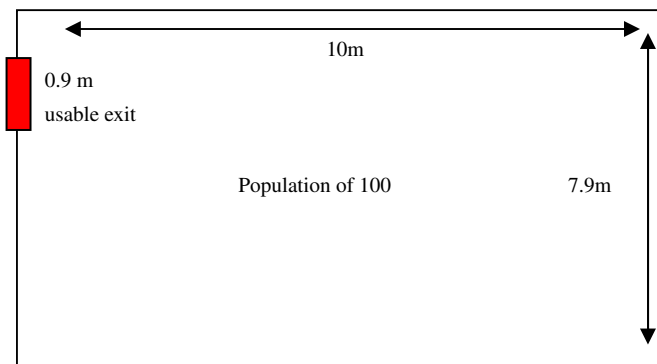


Fig. 7. The geometry used in the hypothetical case.

Table 4

Dynamic doorway width observed during the pedestrian movement from the arena

Dynamic width (% of actual width)	Specific flow (occ/m/s)
75[56–84]	0.92[0.65–1.38]

approximately 1.25 occupants/m². According to the curves employed within the SFPE handbook (see Fig. 1), this should enable near maximum flow conditions to be produced (Table 4).

Table 5 shows that the different flow rates applied have a significant impact on the evacuation times calculated for all of the different modeling methods. In more complex designs, it may be expected that this effect would be reduced as other evacuation factors interact. However, it is not satisfactory to rely on the complexity of the design to compensate for the shortfalls of the data included, or the assumptions on which the methods are based.

As expected, the trends from the three different calculation methods reflect the assumed flow rates (see Table 5). This indicates the importance of these flow rates within relatively simple and complex methods of calculation.

In the next section, the implications of the analysis presented in the previous two sections are discussed in relation to three distinct areas of the fire safety process: regulatory change; engineering recommendations; and computational egress modeling.

6. Discussion

From the data collected, it is apparent that the full width of a doorway may not be available. This reduction in capacity was due to the interaction between the population and the doorway (in the form of the mechanism used to open it). This will be compounded by other behavioral issues relating to the maintenance of personal space.

The under-use of the doorway width available will have serious consequences for the overall doorway capacity available from the structure. It may be incorrect to assume that the full width of the doorway is available for doors not mechanically held open (including self-closing doors). Rather, the engineer should assume that the door will be operating at a reduced capacity.³ A proportion of the population will need to hold the door open, with the rest of the population passing through the doorway as it is held open by others. The doorway width available to the population will then fluctuate according to the extent to which the doorway is opened by individuals (see Fig. 3); i.e. it will depend on the actions of individual occupants, rather than on the physical width of the doorway itself. This new assumption will have important implications.

In the current SFPE guidance on determining doorway flow rates, no reference is made to the nature of the doorway type. Instead, reference is made to the width of the doorway and the density of the population making use of the doorway [1]. This reflects current engineering practice. Indeed, the performances of doors, corridors, aisles and ramps are not differentiated in the calculations [1]. From our analysis, the design of the doorway potentially has an important impact upon the flow rates that can be expected; e.g. whether an individual needs to interact with the doorway, whether the doorway is always fully open, etc.

³ It is not suggested that all doors be mechanically held open as this is unrealistic and may also compromise compartmentation.

Table 5
Evacuation times produced during egress analysis

Origin of data	Observed specific flow rate (occ/m eff. width/s) (occ/ft eff. width/min)	Evacuation times produced (s)		
		EVACNET4	buildingEXODUS ^a	SFPE model
Fruin (arena)	0.92(16.9)	125	126[123–129]	118
SFPE	1.31(24)	85	92[91–94]	83

^a A range of values are produced for buildingEXODUS due to the stochastic nature of the model.

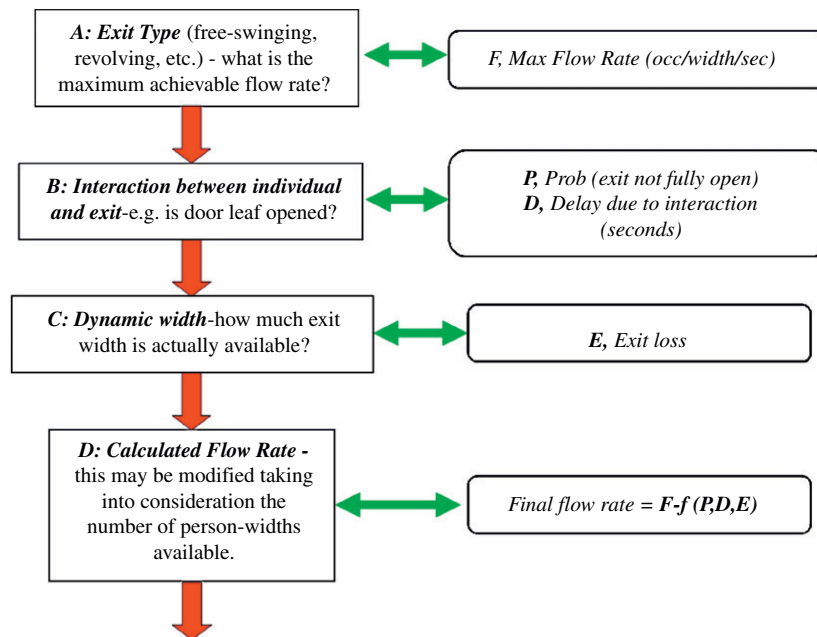


Fig. 8. Possible algorithm for computer model.

The design of the doorway elicits different evacuee behaviors that directly influence the available doorway width. A set of remedial actions could be recommended relating to the different designs of doorways and the potential limiting impact of the occupant interaction with the doorway (i.e. the impact of dynamic width and the delaying impact of the interaction between the door leaf and the evacuee). In such cases, where a door is not mechanically held open, a reduced maximum specific flow rate could be assumed; a reduced exit width assumed; or a maximum flow rate assumed for each exit leaf (for instance, the Fruin figure of 40–60 persons/min). If the impact of dynamic width is included, then the engineering flow rate currently employed appears reasonable for doors that are not mechanically held open.

The impact of these findings upon computer model design will depend upon the underlying assumptions of the model in question [16]. In models that are based around a coarse network (e.g. EVACNET4), the points made here might directly influence the flow rates employed within the model. As demonstrated in Section 7, the flow rates dominate the results produced. Therefore, different flow rates could be employed according to the nature of the doorways being represented within the model. These flow rates should also take into consideration the dynamic width; i.e. the possible loss of doorway width through pedestrian interaction.

In more complex models, where a more detailed representation of the structure is employed, these considerations may be employed at a lower level. In essence, the method incorporated into the model might then be more predictive, *establishing* the flow rate through the doorway mechanism, the interaction of the

individual with the doorway, and the dynamic width produced as a consequence (see Fig. 8).

More data would be required for the development of this type of algorithm. However, these data would be relatively easy to collect and would have other applications beyond modeling (e.g. supporting our understanding of the phenomenon). As mentioned above, in the absence of such fundamental data, these models could simply employ flow rates related to the type of doorway, taking into consideration the possibility of the dynamic width effect.

7. Conclusion

This paper challenges the simple linear relationship between doorway width and flow rate. The data examined suggest that doorway mechanisms influence pedestrian performance. In addition, the continual operation of this mechanism (in this case the commonplace doorway-leaf design) limited the doorway width available, which fluctuated as the population flowed through it. Given this, the term dynamic width is suggested, indicating the manner in which the available (physical) width varies during the use of the doorway. The original term, effective width, identifies a reduction in the available doorway width, through boundary issues. It is contended that in some instances this reduction may be more extreme and dynamic, through the behavior of the evacuees and the nature of the door mechanism. Therefore, the physical width available may fluctuate during use of the exit, with the width actually utilized further reduced by boundary issues.

It is vital that further data be collected on the relationship between doorway width, doorway mechanism and the flow rates that might be expected. These are key elements in determining the overall egress times, especially where large populations are involved. These findings, and the suggested future work, will have an important impact on future code/regulatory changes, engineering guidance and developments in computational modeling and therefore have a significant impact on the safety levels of future building design.

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