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EVACUATION MODELING DEPENDENCE ON INPUT PARAMETERS

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ABSTRACT

One of the cornerstones to performance-based design (PBD) is the assessment of occupant evacuation times from a building in the event of a fire. Considerable progression in the capabilities of egress modeling has led to a fairly comprehensive range of assessment tools for fire protection engineers to evaluate occupant evacuation. Rapid advancements in computer technology have resulted in noticeable improvements in current evacuation software including faster computing times, increased visualization, and simpler user interfaces. Some models also integrate many user options in attempt to implicitly predict human behavior within the fire environment. These sophisticated models simplify a complex and dynamic aspect of occupant evacuation for the user. It is implied that with greater complexity and range of assessment options built into the model comes improved accuracy and higher confidence in the results, which are in turn dependent on the assumptions made and parameters selected by the user.

This paper assesses the application of various modeling techniques to a high occupancy evacuation scenario. A case study will be evaluated using a hand calculation method, movement-optimization model and partial behavioral simulation model. Input parameters to the respective methods will be varied, within appropriate ranges from evacuation literature, to ascertain the significance of assumptions made on the total evacuation time. The variance of parameters will be compared within the methods and compared across the different simulation methods. The focus of this study is to highlight the dependence of current evacuation modeling methods on the user inputs, therefore providing users with a better understanding and awareness of how the evacuation time can vary when these parameters are altered.

INTRODUCTION

The evolution of performance based design (PBD) in fire protection engineering has led to a greater dependence on estimating evacuation times during potential emergency scenarios to determine Required Safe Egress Times (RSET). Reliance on computer evacuation models requires an understanding of the model and of human behavior in fires. Behavior in fire is hard to predict and depends on many parameters including the geometry, the occupants and the relevant fire scenarios. Current models typically rely on the user to simplify the behavioral effects by estimating a time delay or prescribing actions into a computer model, but do not allow for the occupant to perceive and interpret cues. Predictive modeling requires the user to make generalizations and assumptions, such that complexities of occupant evacuation can be simplified into practical input parameters.

As the capability of models is developed, they embed more assumptions into the program or require more user inputs. This requires the user to have a stronger understanding of the settings built into the program. The engineer must evaluate user-defined settings as default options are rarely representative of likely conditions (Gwynne 2010).

In 2005 NIST provided a ‘Guide for Evaluating the Predictive Capability of Computer Egress Models’ (Lord 2005). The guide gives a comprehensive literature review of applicable parameters and a discussion of appropriate use of models. Example scenarios from STEPS and EXIT89 were used to compare the variance and uncertainty of model parameters within the models while comparing with experimental results.

The SFPE Handbook provides a summary on available computer modeling methods and guidance on selecting an appropriate model to fit project requirements (Kuligowski 2008). The chapter provides guidance on model configuration with an example of a high rise office/hotel building. A subsequent paper updates the computer model review contained within the SFPE Handbook (Kuligowski 2010).

Expanding further on the application of predictive evacuation modeling, this paper evaluates a high occupancy case study with hand calculations, a movement-optimization model and a partial behavioral model. These methods are typical approaches that may be used in the fire protection engineering field to determine the RSET. The methods are used to determine the evacuation phase and may incorporate the pre-movement phase. When evacuation and pre-movement times are combined they represent the escape phase (Gwynne 2008). Each method of determining the evacuation times has varying levels of complexity and assumptions. It is typically implied that adding more detail will provide more accurate results, thereby lowering the uncertainty and safety factor needed. This paper provides a comparative case study of different methods for predicting the escape phase of evacuation, but is not a comprehensive review of all scenarios, or all available evacuation programs.

Modeling Methods Used

Hand calculations

Hand calculations are typically conducted based on *SFPE Employing the Hydraulic Model in Assessing Emergency Movement* (Gwynne 2008). This is a simplified set of equations to determine the evacuation phase of the RSET. Occupants move from egress component to egress component based on hydraulic equations. The simplified evacuation equations can be considered optimistic as they maximize flows for occupants passing through egress components. The calculations do not allow for occupants to be treated independently, therefore occupants begin movement and progress as a group.

It requires judgment of the engineer to predict the effects of behavior, including pre-movement decisions, the interaction of detailed building geometry and the occupant's response to fire conditions. The parameters have a significant bearing on the results obtained but are not incorporated into the equations.

Movement-optimization model

Movement-optimization models also do not attempt to incorporate behavioral aspects into their calculation. Occupant travel and flow are optimized to produce the quickest evacuation of the building. Evacnet is a movement-optimization computer model developed at the University of Florida and is public domain software. For this paper the Evacnet4 version is used. Further explanation of the model can be found in the user guide (Kisko 1998). Evacnet uses flow through a coarse network where the building is created as a list of nodes and arcs. Nodes have an initial occupant load and a maximum occupant load, which are connected to adjacent nodes through arcs. Arcs are assigned a travel time and a maximum flow. Occupants are placed in the nodes by the user and travel in a way for each final exit to have generally the same final evacuation time.

The occupants have a global view of the building to find the final exit providing the quickest route. As occupants are treated as a group of people in a node, their characteristics can not be treated individually. Travel time and maximum flow of occupants can not be varied during the simulation.

The network system used by Evacnet allows for the computer to integrate the flow of multiple groups of people at multiple locations, an aspect typically too difficult for hand calculations. The process does require the user to calculate the flow and travel time for each arc.

Partial behavior model

Partial behavior models implicitly account for some behavior aspects. Pathfinder is a partial-behavior model that allows for the user to include different occupant parameters and exit decisions. Pathfinder version 2009.2 is used for this paper. Further information on the modeling techniques can be found in the user guide and technical reference (Thunderhead 2009). The software allows the user to create 3-dimensional building geometry including rooms, doors, stairs and obstructions. Occupants are treated as individuals throughout the simulation. The domain is defined as a continuous network where occupants move through a coordinate-based system. The velocity, location and path of occupants are updated for each time step. Occupants are given a pre-movement time, shoulder width and maximum unimpeded walking velocity. The user can assign parameters to be constant values, uniformly distributed or normally distributed. By default, Pathfinder works by calculating the movement path to the nearest exit for each occupant. However, users have the option to specify exit paths for occupants or groups. Unlike Evacnet, exits may not have the same final time.

Pathfinder calculates movements using two modes: SFPE or steering. SFPE mode calculates movement by using the approach detailed in SFPE for hydraulic egress calculations (Gwynne 2008). The calculation procedure includes modified velocities based on room density and stair geometry. The flow through doors is restricted based on boundary layers and door flow rates. SFPE mode by default allows multiple occupants to occupy the same location. Therefore queues are not seen visually and occupants appear to walk through each other. Collision avoidance can be enabled in SFPE mode so occupants stop when they are obstructed by other occupants.

Occupants in steering mode modify their path and velocity based on inter-person distance and wall locations along their potential pathways. Steering mode takes into account collisions of other occupants and obstructions therefore not allowing occupants to occupy the same space. No flow restriction is imposed on doors, allowing occupants to flow through doors as if they were moving through a room.

DESIGN SCENARIO

Building Layout

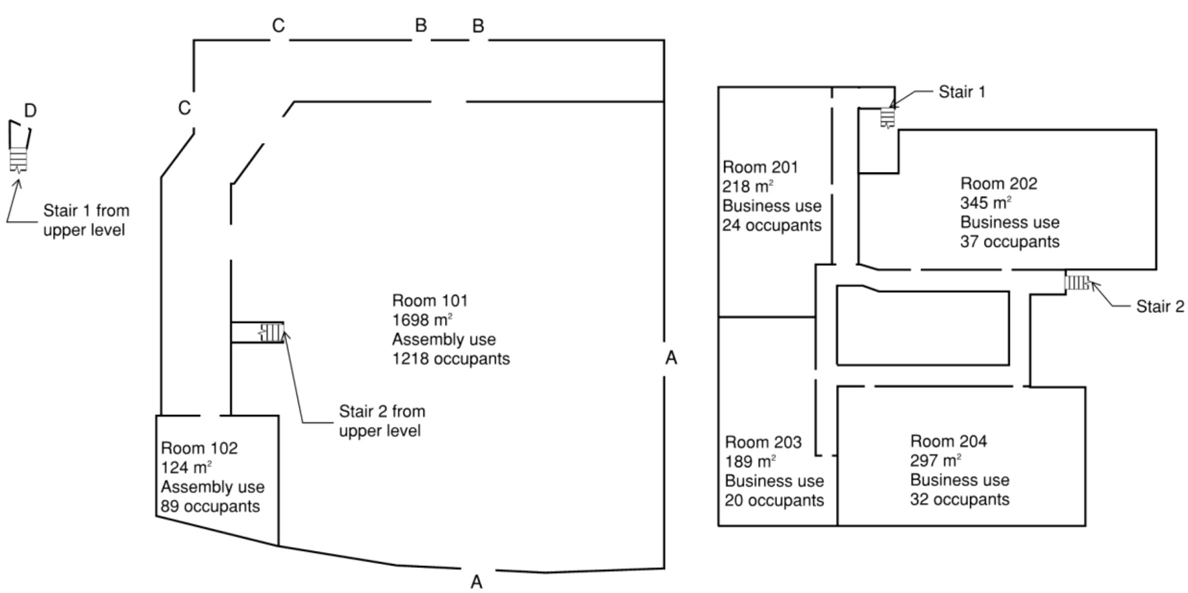
An assembly occupancy case study has been used to ascertain the impact of varying input parameters on the aforementioned modeling methods. The case study is a two story high occupancy building shown in Figure 1, which functions as a large assembly space with offices on the top floor. The lower level contains assembly areas where there is a main room and an adjacent smaller room. Occupant density values are obtained from The Life Safety Code (NFPA 2009). The rooms have a less concentrated assembly occupant density of 0.71 persons/m^2. The upper level contains four rooms at a business occupant density of 0.11 persons/m^2. Upper level occupants have access to two staircases as shown in Figure 1. The building has a total of 1420 occupants.

Figure 1 represents the exact geometry modeled in Pathfinder. For hand calculations and Evacnet, final exits that are close together are grouped to simplify the analysis. The exits are paired because they have similar evacuation paths and final exit times. Figure 1 shows the final exits grouped from A-D.

Hand calculation setup

Occupant travel paths are determined based upon the optimized potential flow of available doors and their initial location. Final exits are groups as shown in Figure 1. Occupants with the same travel path are assumed to move as a group from their initial location to their final exit. Queuing occurs at the final exit, as they are the most restrictive element. Groups using the same final exit are able reach the exit prior to the queue dissipating. Therefore calculations account for consecutive loading of groups at each exit. As a result the movement time comprises the initial travel time of the closest group to the final exit and then the time for the all occupants to pass through the final exit.

A summary of SFPE evacuation equations is provided, further details can be found in 'Employing the Hydraulic Model in Assessing Emergency Movement' (Gwynne 2008). Typical tread and rise of stairs within the mode are 18 cm by 28 cm, respectively.



(a) *(b)*

Figure 1: Layout of design scenario: (a) Ground floor; (b) Upper Floor

Maximum unimpeded walking velocity is 1.19 m/s for level surfaces and 0.95 m/s for stairs. When occupant density is greater than 0.54 persons/m^2, the following equation is used for walking velocity:

$$S=k-akD$$

Where:
S = Travel speed, m/s
k = 1.40 for level surfaces and 1.08 for stairs
a = 0.266
D = Occupant density in persons/m^2

The flow through building elements is calculated by:

$$F_c = F_s W_e$$

Where:
F_c = calculated flow, p/s
F_s = SD with a maximum specific flow of 1.3 for level surfaces and 1.01 for stairs, persons/s/m of effective width
W_e = Effective width, m

A boundary layer thickness of 20 cm for corridors and 15 cm for doors or stairways is used to determine the effective width.

Evacnet model setup

Nodes are created for each initially occupied room. Room 101 is broken up into four nodes due to its size. The rooms are connected with arcs to nodes representing the hallways and stairs. The dynamic capacities of arcs are determined using the SFPE effective width and maximum specific flow explained earlier. The traversal times are found using the SFPE maximum unimpeded walking velocity based on occupant density. Similar to the hand calculations, there are four final exits created, grouped as shown in Figure 1.

Pathfinder model setup

The building is created in Pathfinder with each door, stair, room and corridor represented. Occupants are randomly located in their rooms based on the applicable occupant densities.

Each Pathfinder scenario was performed once. Rerunning the same input from Pathfinder will yield the same results. However, redistributing the occupants and pre-movement distributions will produce different results.

SIMULATIONS

Base Case

A base case is created for each method. The following parameters consistent for each method:

- 1420 occupants
  - Less concentrated assembly use on lower floor
  - Business use on upper floor
- Walking velocity per SFPE equations
- Doorway flow per SFPE equations
- Shoulder width of 46 cm
- No pre-movement time

The base case run for Pathfinder in steering mode uses a maximum unimpeded velocity of 1.19 m/s but does not account for doorway flow or walking velocity governed by SFPE values. No parameters are given a distribution among occupants.

Parameters Varied

Table 1 summarizes the scenarios evaluated for each method.

Occupant Density

Occupant density is varied from 25% to 175% of the initial value in increments of 25% while other parameters are held constant. The base case assembly areas have an occupant density of 0.71 persons/m^2. Therefore, the variation is from 0.18 persons/m^2 to 1.25 persons/m^2. The lower occupant loads are therefore comparable to skating rinks or sales areas above the ground floor while the higher occupant loads are comparable to concentrated assembly use or casinos (NFPA 2009).

Table 1: Model scenarios ran.

	Hand Calculation	Evacnet	Pathfinder, SFPE and Steering
Base Case	X	X	X
Occupant Density		X	X
Velocity		X	X
Shoulder Width			X
Pre-movement distribution			X
Pre-movement, shoulder width and velocity distributions			X

Velocity

An average value for maximum unimpeded walking velocity is 1.19 m/s. The walking velocities are varied from 50% to 175% in increments of 25% of the initial value while other parameters are held constant. The range in unimpeded walking velocities is then 0.60 m/s to 2.08 m/s. The standard deviation of walking velocities is approximately 0.25 m/s (Lord 2005). Therefore scenarios are typically within 2 standard deviations of the mean. However the highest velocities are comparable to maximum values.

Shoulder Width

An average adult shoulder width of 46 cm is used (Predtechenskii 1978). Shoulder widths are varied from 50% to 175% in increments of 25% of the initial value while other parameters are held constant. The range of shoulder widths is from 23 cm to 80 cm. The lower values are comparable to small children while the higher values are comparable to an adult holding a child or light package.

Pre-movement Distribution

Pre-movement times are normally distributed across the population while other parameters are held constant. Simulations are run with standard deviations of 5 s to 25 s in increments of 5 s. This range of standard deviations will lead to results that will produce both queue dominated and pre-movement dominated scenarios.

Pre-movement, shoulder width and velocity distributions

A normal distribution is given to shoulder width, pre-movement and velocity. The constant values established earlier are kept as average values. The occupant density is also kept at the base case value. The shoulder width is given an 8 cm standard deviation. The range of two standard deviations leads to shoulder widths of 30 cm to 62 cm. This corresponds to a shoulder width range from children through adults (Predtechenskii 1978). The velocity is given a 0.25m/s standard deviation, found to be consistent with all age groups (Lord 2005). The range of two standard deviations leads to occupant's unimpeded walking velocities of 0.69m/s to 1.69m/s.

Pre-movement is given a 10 s standard deviation. This was determined by taking a pre-movement standard deviation where pre-movement shows an effect from the distribution, but the time is not governed by pre-movement.

RESULTS

Model Comparisons

Exit distributions

The occupant distribution per exit is shown in Table 2. Evacnet optimizes exit distribution for quickest evacuation times while hand calculations involve the user distributing the occupants but involve a similar approach of assuming occupants maximize their exits. Pathfinder chooses the shortest path. Therefore Table 2 shows more occupants in Room 101 go directly outside, instead of walking a further distance to exits with less queuing.

Table 2: Exit Distribution.

Method	Exit A	Exit B	Exit C	Exit D
Hand Calculation	46%	20%	30%	4%
Evacnet4	46%	20%	29%	5%
Pathfinder, SFPE and steering	56%	17%	22%	5%

Base case movement times

The base case movement times are shown in Table 3. The largest variation is seen in the steering mode of Pathfinder. This mode uses a different method of determining velocity and flow of occupants as previously explained.

The three modes that use SFPE velocity and flow calculations are of comparable times. A travel distance for the first group to reach the door was assumed for Evacnet and hand calculations. While Evacnet and hand calculations maximize flow, Pathfinder's treatment of occupants as individuals allows for dispersion of occupants throughout the area allowing occupants in close proximity to exits to have relatively no travel time.

Table 3: Base Case Evacuation Times.

	Hand Calculation	Evacnet	Pathfinder (SFPE)	Pathfinder (Steering)
Evacuation Times	109	101	103	78*

*Steering mode does not use same velocity and flow equations as other methods.

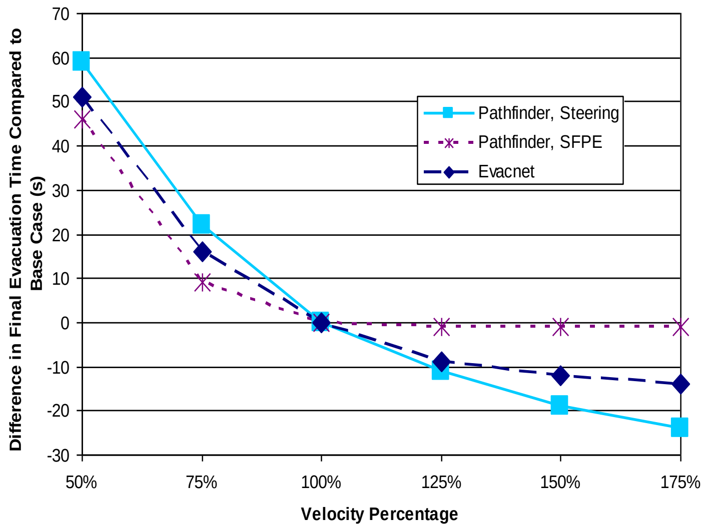


Figure 2: Difference in final evacuation time compared to base case results for velocity variation in Evacnet and Pathfinder

Velocity

The effects of modifying the maximum unimpeded velocity when compared to the base case results are shown in Figure 2 for Evacnet and Pathfinder. All methods have a similar trend. Evacnet changes the exit distribution for each case to optimize movement times. Pathfinder keeps the same exit distribution and therefore exits where occupants have longer travel distances are impacted more with velocity modifications.

As expected the models predict similar deviation from the base case as occupant velocity is reduced, due to occupant travel to the exit dominating the final time. As mentioned earlier, door flow rates for Pathfinder in steering mode are not governed by SFPE equations. Therefore as occupant velocity is increased, improved final exit times are predicted by the steering model over the base case, because occupants are able to move through the exit with less restriction.

At higher occupant velocities, Pathfinder in SFPE mode predicts insignificant increases in exit time over the base case, because the prescribed maximum flow through the exit dominates. The variation from the base case predicted by Evacnet at higher occupant velocities is simply attributed to the group reaching the exit earlier, at which point exit flow dominates.

Density

The effect of occupant density is shown in Figure 3 where movement times are compared to the base case results.

As expected, at lower densities the travel time governs the movement time. The variation in base case exit times for Pathfinder in SFPE or steering mode is approximately 30 s. At lower occupant densities (25%) the variation in exit time reduces to 5 s. This is expected as travel times will be similar due to the same maximum unimpeded walking velocity and less influence by the different methods of predicting exit flow.

Figure 3 indicates that at higher occupant densities both Pathfinder (Steering) and Evacnet predict similar variation over their respective base case results. Pathfinder (SFPE) predicts a greater variation due to exit flow influences at the higher occupant densities. Although Evacnet and Pathfinder (SFPE) both incorporate the SFPE door flow algorithm and also predicted similar times for the base case exit time, Evacnet is less influenced by higher densities as a result of occupant redistribution to exits in order to optimize movement times.

<u>Parameter Effect in Pathfinder</u>

Parameter comparison

Figure 4 compares shoulder width, velocity and occupant density for Pathfinder in steering mode when each parameter is varied while others are held constant. The movement times are compared to base case results.

Shoulder width results for SFPE mode are negligible as collision avoidance between occupants is not

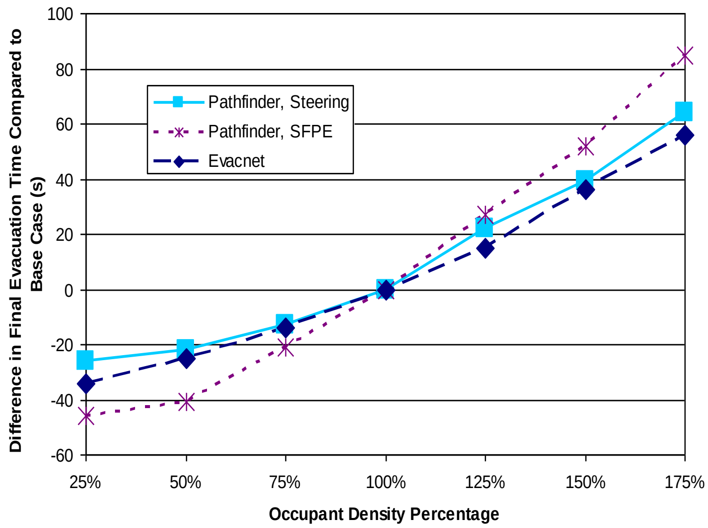


Figure 3: Difference in final evacuation time compared to base case results for occupant density variation in Evacnet and Pathfinder

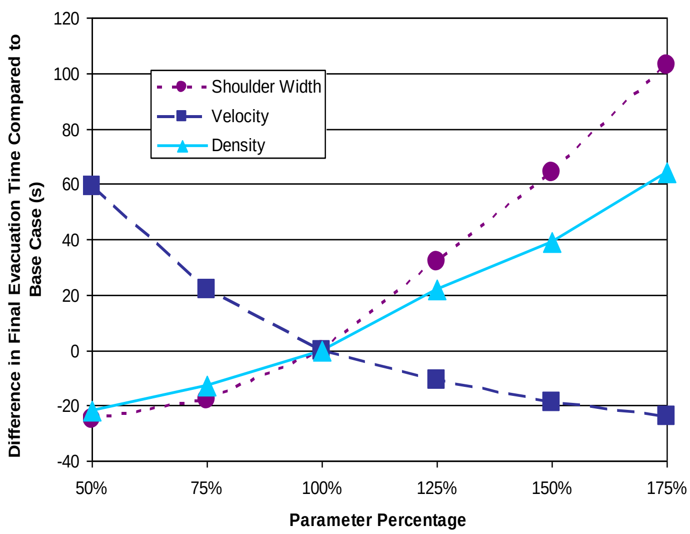


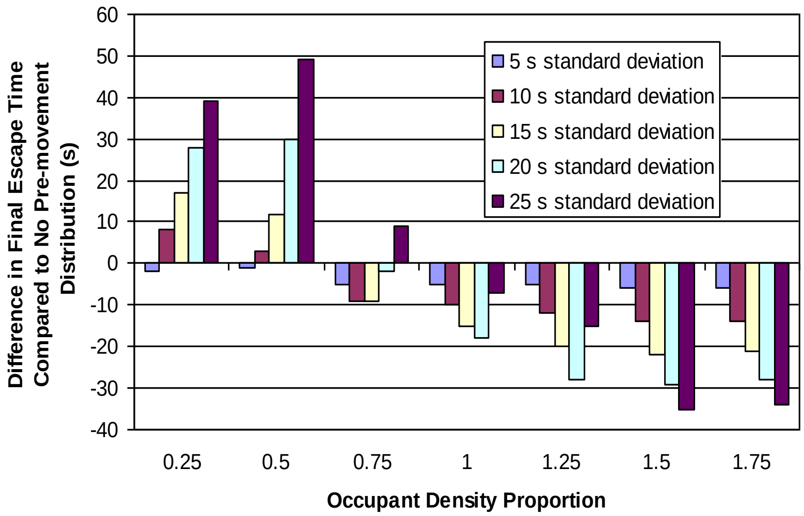
Figure 4: Difference in final evacuation time compared to base case results for parameter variation in Pathfinder steering mode

assessed for in this study. When the shoulder width, velocity and occupant density variables are low the travel time is more prevalent. As the parameter percentages increase the shoulder width and density become dominating factors due to the influence on exit flow.

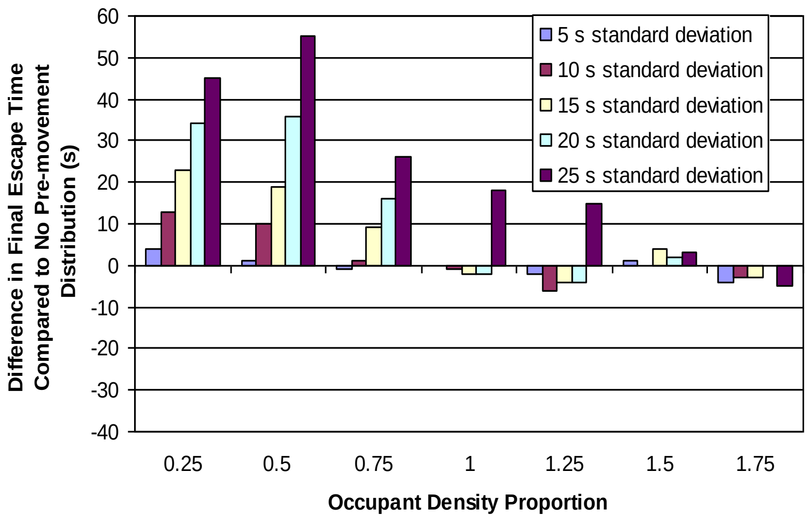
Pre-movement distributions

A normal distribution is applied to pre-movement times for different occupant densities. Figure 5a represents the difference when the standard deviation is varied for SFPE mode. The escape times are compared to simulations where a constant value pre-movement is imposed. At low densities, having a wide distribution increases escape times as the final time is no longer determined by queuing at the final exit but by occupants with large pre-movement times. Under the higher occupancy scenarios the pre-movement distribution with greater spread improves escape times due to exit flow rates occurring earlier in the simulation. Occupants with longer pre-movement times are able to reach the exit before the queue has dissipated.

A similar effect of pre-movement distribution for lower occupant densities is shown in Figure 5b for Pathfinder in steering mode. However at higher densities there is minimal increase in the escape time. Occupants in steering mode determine their path and velocity based on collisions of walls and other occupants. When a pre-movement distribution is applied, moving occupants attempt to navigate



(a)



(b)

Figure 5: Difference in final escape times compared to no pre-movement distribution at occupant density levels for varying standard deviations in (a) SFPE mode (b) steering mode

around occupants that have not begun traveling. Occupants with larger pre-movement times close to a final exit create obstacles that decrease or stop the movement of occupants as they egress. This behavior is seen in Figure 6 where an occupant has stopped moving because there are two occupants with longer pre-movement times in front of them that have not yet begun moving.

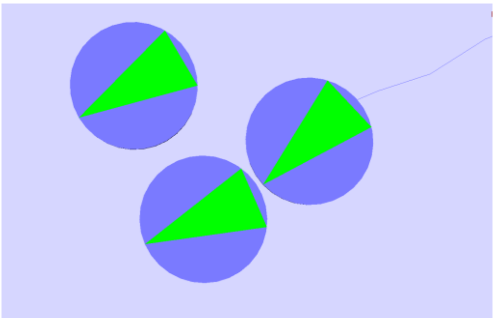


Figure 6: Intermediate queue effect for Pathfinder in steering mode

The effect of intermediate queuing was found to occur in the Simulex evacuation model with high occupant densities (greater than 1.00 persons/m^2) and high pre-movement variations (Spearpoint 2004). Spearpoint states intermediate queues to be unlikely in real evacuation scenarios as occupants would navigate around still occupants or the movement surrounding still occupants would cause them to begin walking.

Figure 7 shows the amount of occupants remaining in the building for different pre-movement distributions for Pathfinder in SFPE mode. A 60 s pre-movement time is used as the average pre-movement time. With a constant pre-movement time the flow out of the building is generally constant after 60 s. Assigning a pre-movement distribution with a greater spread allows occupants to exit the building earlier as a result of the maximum exit flow being achieved earlier in the simulation. The final escape times decrease as standard deviation increases, except for a standard deviation of 25 s. This is consistent with Figure 5b and earlier discussions, where the higher standard deviation causes the final evacuation time to be governed by a small group of occupants with high pre-movement times which influence the overall evacuation time.

Flow out of the building for Pathfinder in SFPE mode and steering mode is shown in Figure 8. The lower base case movement time for steering is seen as occupants have an improved exit flow than that imposed by SFPE mode. When a normal pre-movement distribution with 25 s standard deviation is included, the intermediate queue effect is seen as steering takes longer to reach a steady flow than SFPE mode. When a steady flow is achieved in steering mode, this is a greater rate than that achieved in SFPE mode. The two movement methods converge at the end of the simulation to give similar final evacuation times because the scenario is governed by occupants with high pre-movement times.

Distributed Parameters

The incorporation of distributions for pre-movement, shoulder width and velocity increased the escape time 17 s for steering mode and decreased the time 5 s for SFPE mode when compared to the base case

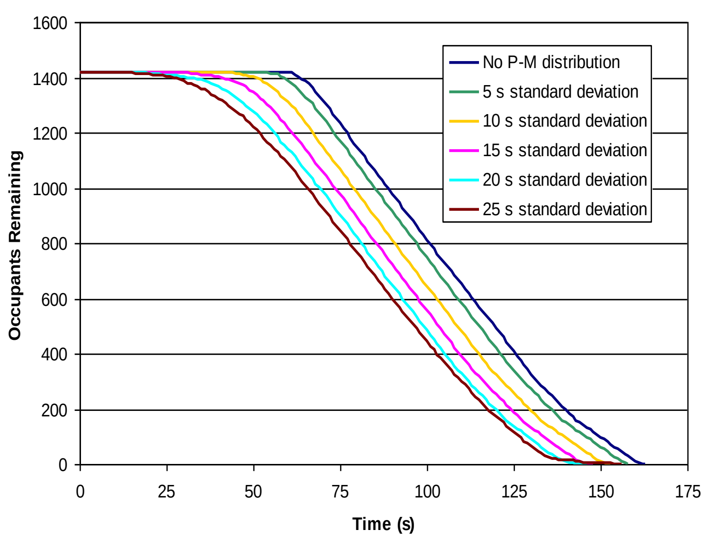


Figure 7: Occupants remaining in simulation over time for different pre-movement normal distributions in SFPE mode

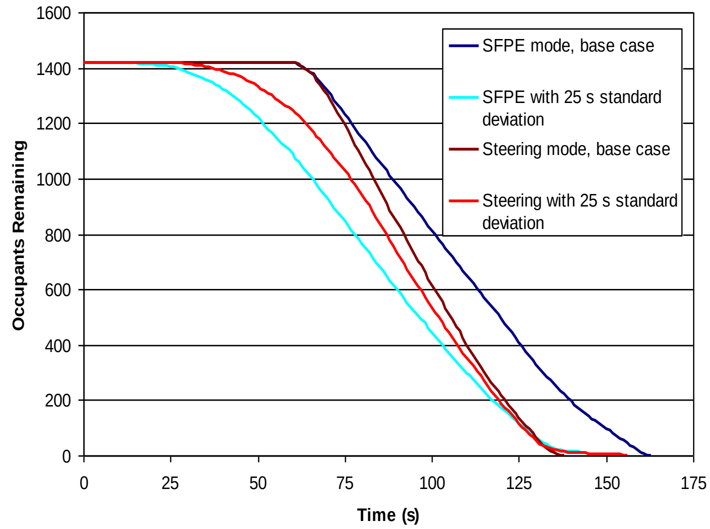


Figure 8: Occupants remaining in simulation over time for Pathfinder in SFPE and steering mode with and without pre-movement normal distribution

scenarios, where the input parameters were represented by constant values. Therefore, for this particular case study, applying distribution to the subject input parameters represented a change of approximately 22 percent and 5 percent in the escape time, for the steering and SFPE methods respectively. Further results also imply that incorporating the shoulder width distribution had a minimal effect on the comparison. This is expected as smaller occupants negate the influence on flow of larger occupants. For this case, the variation between the simulations with and without parameter distributions is attributed to the occupant velocity distribution. Occupants in steering mode had a greater effect from velocity distributions as their speed is altered by collisions with slower occupants.

CONCLUSION

The methods used to predict the escape time provided good agreement, with exception of the partial behavior model (Pathfinder) in steering mode. The case study involves a high occupancy scenario with minimal exit capacity; therefore the other methods are governed by exit flow limitations, whereas the steering method is more affected by occupant parameters.

Both Evacnet and Pathfinder (SFPE) utilize similar methodologies to flow through constrictions. However, Evacnet's optimization model results in less variation from the base case where occupant densities are increased. This assumes the behavior where occupants select an alternative exit to minimize queuing.

The study shows that where a simulation model is used to predict escape times from a building, the selection of the parameters describing the input distributions can have significant bearing on the results obtained. Further discrepancy in results can be achieved where the user is not aware of the variation gained by the different modeling methods such as exit choice, movement calculations or network structure. The user should be cognitive of the application and limitation of such models and be wary of un-realistic affects (intermediate queuing) influencing results.

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