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USE OF PATHFINDER IN THE STUDY OF OCCUPANT MOVEMENT IN STAIRWELLS

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ABSTRACT

The goal of this paper is to compare empirical egress data to data produced by computer egress models. The empirical egress data presently considered consists of video recordings of unannounced fire drills conducted in several high-rise office buildings. The computer egress modeling data consists of a series of model runs to assess merging for a simple building configuration with one stairwell using the Pathfinder egress modeling software. Similar to the empirical egress data, the Pathfinder results provide an outflow rate for a merging event which is generally less than the sum of the two inflow rates. Quantitatively, the empirical and modeling data are in reasonable agreement.

INTRODUCTION

Emergency evacuations from buildings, particularly high-rise buildings, are relatively rare in the United States. An individual who works in a high-rise office building will likely go many years without experiencing an emergency evacuation. Nevertheless, on the rare occurrence of an emergency evacuation, there may be a significant threat to life safety.

The goal of this paper is to compare empirical egress data to data produced by computer egress models. The empirical egress data presently considered consists of video recordings of unannounced fire drills conducted in several high-rise office buildings across the U.S. Several-hundred hours of these videos were analyzed, and pertinent data relevant to the egress of each occupant was recorded in spreadsheet files produced by the National Institute of Standards and Technology (NIST) (Kuligowski and Peacock 2010).

The empirical egress data gathered by NIST was used as a part of a 3-year research grant at the University of Maryland. These 3 years of research produced 4 Master's theses and numerous technical papers and presentations. Each of these publications involved the study of one or more parameters of occupant egress, and many of them included comparisons of empirical data to computer modeling data. This paper will focus on the study of occupant merging behavior during egress, particularly as studied by Campbell (Campbell 2012) and Leahy (Leahy 2011).

The computer egress modeling data presently considered consists of a series of model runs performed in the Pathfinder egress modeling software. Stairwell geometry was created in the software so that the model results could be compared to the empirical data.

OVERVIEW OF OCCUPANT MERGING

During egress from a high-rise building, occupants use the stairwell as their primary path to exit the building. On any given landing within the stairwell, two flows of people may be present: the flow of people descending the stairs from above, called the stair flow, and the flow of people entering the stairwell from that floor, called the floor flow. When these two flows meet on the stair landing, a merging event occurs where the two flows combine into a single outflow of people leaving the stair landing.

A principal reference in the field of egress modeling is the hydraulic egress model presented by Gwynne and Rosenbaum in the SFPE Handbook. The model estimates the required safe egress time (RSET) by calculating the time necessary to move from egress component to egress component until each occupant has completed egress from a building. The key equations that govern the model are equations for speed and flow, both given as a function of occupant density (Gwynne and Rosenbaum 2008). Specific to merging, the hydraulic model operates under a set of rules to determine the density and flow rates of occupants following a transition point. When assuming that the width of an egress component is constant, the rules can be summarized by Equation 1.

$$F_{out} = \sum_{i=1}^{n} F_{in_i} \tag{1}$$

Where:
F_{out} = Outflow rate leaving the transition point
F_{in} = Inflow rate entering the transition point
N = Number of flows entering the transition point

Based on Equation 1, the hydraulic model would predict that the outflow rate from a typical merging event on a stair landing would be equal to the sum of the stair and floor flow rates. Despite this prediction, preliminary studies and observations have shown that this merging event is a significant source of inefficiency in building egress (Leahy 2011) and that the outflow rate from a merging event is generally less than the sum of the flow rates entering the merging event (Campbell 2012). This reduction in flow rate increases the time for occupants to navigate through each stair landing, thus increasing the overall egress time for the building. Furthermore, this inefficiency can prevent occupants from entering the stairwell due to a stoppage of the inflow (queuing).

OVERVIEW OF EMPIRICAL EGRESS DATA

The empirical data consists of numerous video recordings of occupant egress within stairwells of high-rise buildings. The data consists of recordings taken from seven stairwells from four different buildings. This data was gathered through cameras positioned to view the stair landing on alternating floors. The entrance and exit time of each occupant was recorded for each camera view, as shown in Figure 1. Thus, an occupant's progress toward the exit could be monitored each time they pass through a camera view. Additionally, the cameras allowed the floor of origin of each occupant to be determined. Other pertinent data, such as the gender of the occupant, and the lane of the stairwell that they traveled through each camera view was also recorded. While viewing the videos, any qualitative trends or behaviors exhibited by the occupants were noted, as this information is impossible to learn from the spreadsheets alone.

Evacuee #	Location	Handrail	Treads	Enter Time		Exit Time	
	I O M	I O B A		(min)	(sec)	(min)	(sec)
1	O		.	16	48.5	16	51.54
2	O		.	17	2.68	17	11.83
3	O	O	3	17	5.42	17	13.63
4	O		3	17	9.52	17	14.13

Figure 1: Sample Egress Data From NIST Spreadsheets.

OVERVIEW OF PATHFINDER MODEL

Pathfinder is a computer egress model developed by Thunderhead Engineering. The present analysis was conducted using the 2011 edition of Pathfinder, though the model is generally updated every year Pathfinder models occupant movement through a continuous 3D geometry with an underlying 2D triangulated surface used as an evacuation mesh. All occupants in the model move along the evacuation mesh through a path generation algorithm that generates multiple waypoints on the way to the final destination. Pathfinder offers two simulation modes which govern occupant movement: SFPE mode and steering mode. SFPE mode operates under the guidelines of the hydraulic model presented in the SFPE Handbook (Gwynne and Rosenbaum 2008). The SFPE mode governs occupant movement and egress time using a flow model that calculates the time for occupants to travel through doors, stairs and corridors. Steering mode uses a set of complex algorithms to determine the occupant path, thus readers are referred to (Pathfinder Technical Reference Guide) for a detailed explanation. In short, Pathfinder uses the "A*" search algorithm, which generates a series of jagged lines from each occupant to the final destination. The program then smoothens the intersections of the jagged lines using a technique called "string pulling." Pathfinder places waypoints at each of these intersections, and these waypoints serve as intermediate goals for the occupant on the way to the final destination. Once the path is generated, the occupant begins one of the following four movements: seek, separate, avoid walls or avoid occupants.

The program assigns a cost to each of these movements that is recalculated at a designated interval, and the occupant chooses the lowest cost movement. The seek movement simply follows the generated path. The separate movement seeks to maintain a desired distance from other occupants. The avoid walls and avoid occupants movements seek to avoid physical collisions with walls and occupants respectively. For all movements except seek, a movement vector is created to move the occupant off the original path, accomplish the goal of the movement (separate or avoid a collision), and then redirect the occupant's path to the next waypoint. Again, Pathfinder assigns a cost value to perform each of these movements and chooses the lowest cost option every time the program recalculates.

Qualitatively, the steering mode can be summarized by this description from the technical reference guide:

"Pathfinder uses a combination of path planning, steering mechanisms, and collision handling to control occupant motion. Each Pathfinder occupant maintains a path connecting their current position to a point (or room) corresponding to their current goal. This path controls the route the occupant takes during the simulation. Other factors, such as collisions with other occupants, may cause the occupant to deviate from their intended route, but the motion of the occupant will roughly conform to their chosen path. If the distance between the occupant and the nearest point on the path exceeds a threshold value, the path is regenerated to accommodate the new situation (Pathfinder Technical Reference Guide).

CALCULATION OF FLOW RATE

The principal parameter used in this analysis of occupant merging behavior is the flow rate. Several distinct flow rates are considered: stair flow, floor flow, and outflow. The stair flow is the flow rate of occupants entering the landing from the stairs above. The floor flow is the flow rate of occupants entering the landing from the floor being considered. The outflow is the total flow rate of occupants leaving the landing to the stairs below. Each of these flow rates is given in persons per second.

In this analysis, the flow rates are generally considered in ten second intervals that encompass a period of merging between stair and floor occupants on a given stairwell landing. The flow rate is calculated by dividing the number of occupants to enter the landing during the time period in question by the difference in time between the first and last occupant. Only periods of merging that occurred without queuing of occupants are considered. A more detailed explanation of the calculation of the flow rate is given in (Campbell 2012).

In most cases, the sum of the stair and floor flow rates (the total inflow rate) was greater than the outflow rate. Because this does not follow the behavior predicted by the hydraulic model (Gwynne and Rosenbaum 2008), the actual outflow was divided by the total inflow rate (which would be the expected outflow in the hydraulic model) and multiplied by 100 to get the flow ratio, as shown in Equation 2. This calculation was done for all merging events and serves as the main parameter for later analysis.

$$FR = \frac{F_{out}}{\sum_{i=1}^{n} F_{in_i}} \times 100 \quad (2)$$

Where:

FR = Flow Ratio

F_{out} = Outflow rate leaving the transition point

F_{in} = Inflow rate entering the transition point

N = Number of flows entering the transition point

RESULTS OF EMPIRICAL EGRESS DATA

Of the seven stairwells analyzed, 102 merging events were found. Only merging events where no queue of occupants formed were considered. For a further explanation of queued merging, readers are referred to the SFPE Handbook and work by Leahy (Leahy 2011). All of these events were analyzed to determine each of the flow rates and the flow ratio. A distribution of the flow ratio for all merging events is shown in Figure 2.

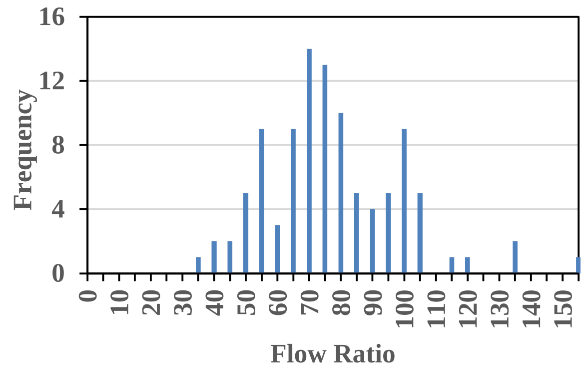

Figure 2: Distribution of Flow Ratios.

The mean flow ratio and standard deviation for each stairwell analyzed is given in Table 1. The stair designations were given by NIST (Kuligowski and Peacock 2010) but are not pertinent to this analysis.

Table 1: Summary of merging data for each stairwell.

Stair	Number of Merging Events	Flow Ratio	Standard Deviation
4A	15	68.1	16.3
4B	6	83.8	16.1
5A	12	67.0	22.7
5B	9	63.6	28.1
7.3	15	69.0	27.7
8N	24	81.0	20.7
8S	21	81.7	18.7
Total[1]	102	75.6	23.0

ANALYSIS OF EMPIRICAL EGRESS DATA

The data presented in Figure 2 and Table 1 reveals that the mean flow ratio for all merging events considered was approximately 75. The means that, on average, the outflow rate from all merging events was 75% of the sum of the inflow rates.

An extensive analysis of why the flow ratio is not 100 as predicted by the hydraulic model, and why this apparent inefficiency in occupant merging behavior exists is given in (Campbell 2012) and (Leahy 2011). The goal of the present analysis is to compare the results of the empirical data analysis to the computer egress modeling analysis and determine if the model successfully replicates the occupant movement recorded in the empirical data.

[1] Flow ratio and standard deviation are for all merging events. Stair designations were assigned by NIST (Kuligowski and Peacock 2010).

PATHFINDER EVACUATION MODELING

Sample geometry was constructed in Pathfinder to replicate merging events from the NIST data. The stair was constructed using similar dimensions of those found in the empirical data. A picture of the geometry is shown in Figure 3 and Figure 4. Two rooms were added to the geometry, and the appropriate number of occupants was added to each room for each event. One room provided the source of people for the stair flow and the other provided people for the floor flow, and a random number between 2-7 occupants was assigned to each room. Through a trial and error process, it was found that flows of more than 8 occupants caused a queue to form when the group moved onto the stairs. Thus, the number of occupants for each flow was limited to 7 to prevent queuing. Each of the rooms was positioned so that both flows would reach the stair landing at approximately the same time. 20 separate trials were run with a different combination of occupants in each trial. For each trial, the Pathfinder simulation was run using the steering mode.[2] All model inputs were set to the Pathfinder default settings.

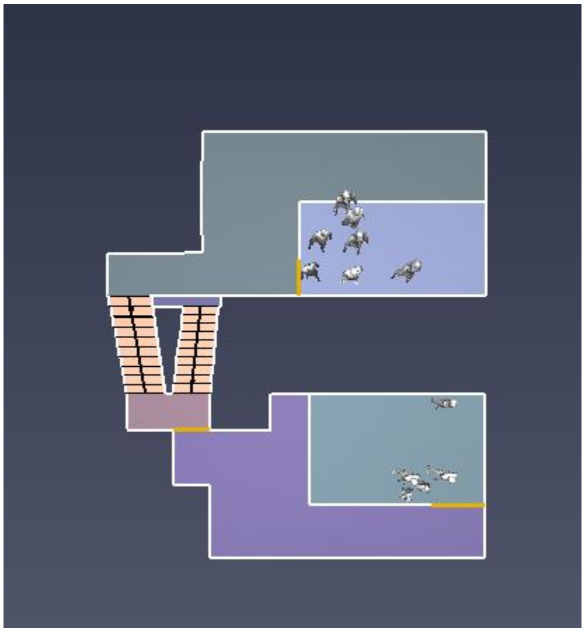

Figure 3: Pathfinder geometry (plan view) shown with sample occupants.

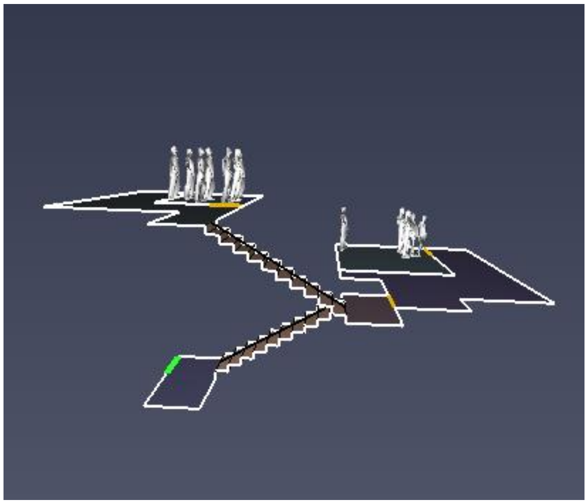

Figure 4: Pathfinder geometry (side view) shown with sample occupants.

ANALYSIS OF PATHFINDER MODELING

A summary of the different occupant combinations and corresponding flow ratio for each event is given in Table 2. The mean flow ratio and standard deviation for all 20 of the Pathfinder merging events is given in Table 3.

Table 2: Summary of 20 Pathfinder merging events.

Event	Floor Occupants	Stair Occupants	Flow Ratio
1	6	5	68.18
2	2	3	52.00
3	5	3	65.85
4	4	6	112.96
5	5	4	80.39
6	3	2	86.84
7	5	5	72.41
8	6	3	64.44
9	7	7	72.84
10	3	6	76.92
11	3	5	102.27
12	6	2	97.30
13	5	6	85.19
14	7	6	76.81
15	3	6	76.60
16	6	4	82.98
17	2	2	76.19
18	5	2	91.67
19	2	7	84.21
20	3	3	94.87

[2] A more in-depth analysis of the Pathfinder simulations, including simulations using the SFPE mode can be found in (Campbell 2012).

Table 3: Statistical data for Pathfinder merging events.

Mean Flow Ratio	Standard Deviation
81.05	14.21

Similar to the empirical egress data, the Pathfinder modeling data shows that the outflow rate from a merging event is generally less than the sum of the two inflow rates. In other words, most of the merging events in the Pathfinder analysis had a flow ratio less than 100. The mean flow ratio for the 20 Pathfinder merging events was approximately 81, with a standard deviation of approximately 14.

COMPARISON OF EMPIRICAL AND MODELING RESULTS

Qualitatively, both the empirical and modeling data show that the outflow rate from a merging event is less than the sum of the inflow rates to the merging event. This differs from the prediction made by the hydraulic model that the outflow rate from a merging event should equal the sum of the two inflow rates.

Quantitatively, the empirical and modeling data are in reasonable agreement. The mean flow ratio for all merging events in the empirical data is approximately 75 with a standard deviation of 23, while the mean flow ratio for all merging events in the modeling data is approximately 81, with a standard deviation of 14. Given the general inconsistencies encountered when studying human behavior, the difference between these two numbers appears to be insignificant. Furthermore, the mean flow ratios for each data set are within one standard deviation of each other, indicating a high degree of agreement between the sets of data.

CONCLUSIONS

Similar to the empirical egress data, the Pathfinder results provide an outflow rate for a merging event which is generally less than the sum of the two inflow rates. Quantitatively, the empirical and modeling data are in reasonable agreement.

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