ABSTRACT

Title of Document: Occupant Merging Behavior During Egress From High Rise Buildings

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Occupant merging behavior on stairwell landings is analyzed through the study of evacuation videos. Both flow rate and transit time analyses are conducted. Data is compared to the hydraulic model, which is presented in Chapter 3 of the SFPE Handbook. It is found that the flow ratio, which is the actual outflow rate from a merging event divided by the expected outflow per the hydraulic model, is on average 75%. The transit ratio, which is the normal transit time of the stairwell landing divided by the merging transit time, is found to be 0.67 and 0.70 for the floor and stair flows, respectively. Empirical data is compared to data collected from the Pathfinder 2011 egress model. Causes and influencing factors of occupant merging are proposed.

OCCUPANT MERGING BEHAVIOR DURING EGRESS FROM HIGH RISE BUILDINGS

By

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1 Corinthians 9:24-27.

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1. INTRODUCTION

Emergency evacuations from buildings, particularly high-rise buildings, are relatively rare in the United States. A person 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 and dangerous threat to life safety. The goal of this paper, along with any other study of human behavior in fire, is to better understand how people act in emergency situations. The primary benefit of this understanding is improved computer egress models, but also improved life safety in buildings.

This paper aims to study people movement in stairs during egress from high-rise buildings. 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. Preliminary studies and observations have shown that this merging event is a significant source of inefficiency in building egress [1]. Specifically, flow rates of groups of people leaving a merging event are less than the sum of the two flow rates of the groups entering the merge. 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 could prevent occupants from entering the stairwell due to a stoppage of the inflow (queuing). Such an occurrence would be extremely hazardous on or near the fire floor(s).

The following research is the final part of a three-year grant from the National Institute of Standards and Technology (NIST). Previous work from the same grant by Andrew Leahy established that the merging inefficiency described above was observed experimentally [1]. One of the aims of this paper is to verify that the inefficiencies described by Leahy do exist, and to subsequently offer possible explanations for why they exist. This knowledge can then be used to improve merging behavior in computer evacuation models, and also potentially improve building design and evacuation procedures. Current building evacuation models are limited in that many do not account for human decision making, or if they do, the decision making process is not based on empirical data. The data presented in this paper should provide a good resource to model developers to improve how evacuation models address mergers.

As a result of improved computer evacuation models, the required safe egress time (RSET) for buildings can be more accurately determined. The RSET is the time required for building occupants to travel from their starting location to a location of safety. Generally the RSET is the time for occupants to completely exit the building. Merging behavior on the stairwell can prevent occupants from moving towards the exit, thus increasing the RSET. This is seen in two different ways: First, the merging event can increase the time for occupants to move through the stairwell landing on each floor. This additional time, when compounded over a tall building, can significantly increase egress time. Secondly, the merging event can cause a stoppage in flow that prevents occupants from entering the stairwell. This is particularly detrimental to occupants on the floor of a fire. Both of these phenomena will be explored in this paper. With an improved calculation of the RSET, the life safety of building occupants can be analyzed by comparing the RSET to the available safe egress time (ASET) available to occupants. The ASET is the time from ignition of a fire until the route of evacuation is untenable. By keeping the RSET below the ASET, the life safety of building occupants is ensured.

2. BACKGROUND INFORMATION

2.1 FIRE PROTECTION LITERATURE

A primary reference in analyzing egress from buildings is the “Emergency Movement” chapter in the SFPE Handbook [2]. The authors describe what is called the hydraulic model of emergency egress, which is a method used to calculate evacuation times from buildings. This model utilizes expressions that relate observed data to a hydraulic approximation of human flow. The model is first order in nature, meaning it is intended to give only a rough approximation of the egress time. The model does not consider human behavior or decision-making, but rather characteristics of building occupants such as density, velocity and flow rate. These characteristics are related to each other through a series of equations that yield speed as a function of density and flow rate as a function of speed and density. The relationship between speed and density is shown in Figure 1 and the relationship between flow rate and density is shown in Figure 2. Generally, density is defined as the number of people per unit area, velocity as the distance traveled per unit time, and flow rate as the number of people passing a certain point per unit time. These relationships are used with additional information about the egress components to calculate the velocity and flow rate of occupants throughout building egress.

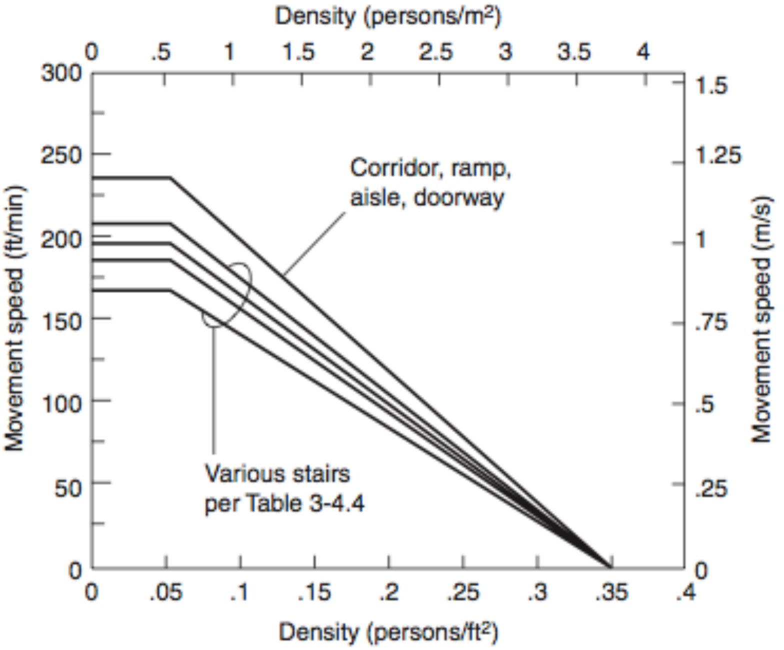


Figure 1: Evacuation speed along line of travel as a function of density. [2]

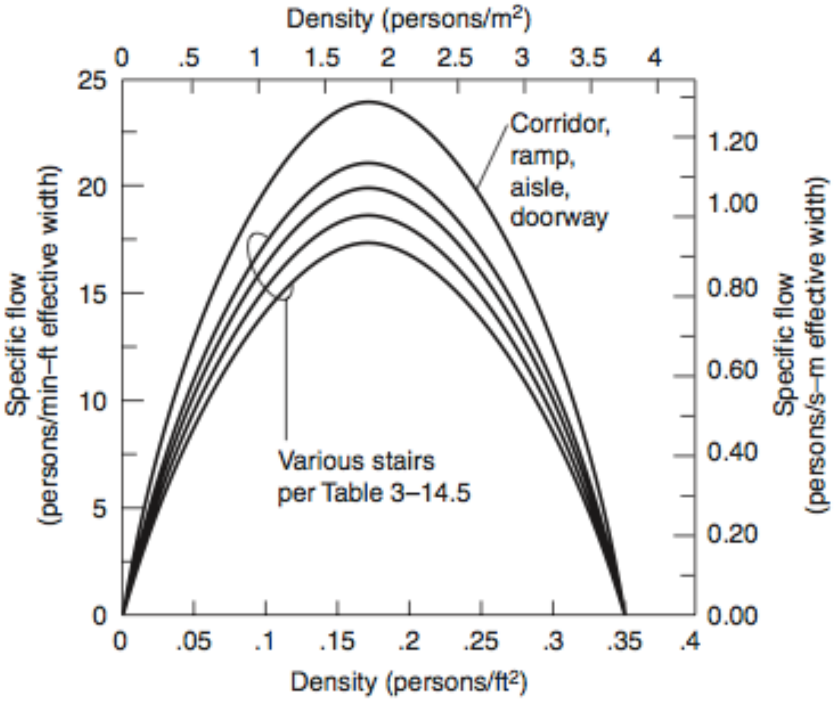


Figure 2: Specific flow rate as a function of density. [2]

With knowledge of occupant velocity and flow rate, it is possible to calculate the time required to navigate any egress component. This time is simply the number of people using that component divided by the specific flow. Knowing the time to traverse each egress component allows the total egress time of the building to be calculated.

Relevant to merging, the model gives the following rules for densities and flow rates following the passage of a transition point:

“

1. The flow after a transition point is a function, within limits, of the flow(s) entering the transition point.
2. The calculated flow, F_c, following a transition point cannot exceed the maximum specific flow F_{sm}, for the route element involved multiplied by the effective width, W_e, of that element.
3. Within the limits of Rule 2, the specific flow, F_s, of the route departing from a transition point is determined by the following equations. [2]

$$\boldsymbol{F_{s(out)}} = \frac{\boldsymbol{F_{s(in-1)} W_{e(in-1)} + F_{s(in-2)} W_{e(in-2)}}}{\boldsymbol{W_{e(out)}}} \qquad \textbf{Equation 1}$$

Where:

$F_{s(out)}$= specific flow departing from transition point [p/s-m]

$F_{s(in)=}$ specific flow arriving at transition point [p/s-m]

$W_{e(in)=}$ effective width prior to transition point [m]

$W_{e(out)=}$ effective width after passing transition point [m]

The effective width is the clear width of the stair minus any boundary layer components.

The subscripts (in-1) and (in-2) indicate the values for the two incoming flows.

Additionally:

1. Where the calculated specific flow, F_s , for the route(s) leaving a transition point, as derived from the equations in rule 3, exceeds the maximum specific flow, F_{sm} , a queue will form at the incoming side of the transition point. The number of persons in the queue will grow at a rate equal to the calculated flow, F_c, in the arriving route minus the calculated flow leaving the route through the transition point.
2. Where the calculated outgoing specific flow, $F_{s(out)}$, is less than the maximum specific flow, F_{sm}, for that route(s), there is no way to predetermine how the incoming routes will merge. The routes may share access through the transition point equally, or there may be total dominance of one route over the other. For conservative calculations, assume that the route of interest is dominated by the other route(s). If all routes are of concern, it is necessary to conduct a series of calculations to establish the bounds on each route under each condition of dominance." [2]

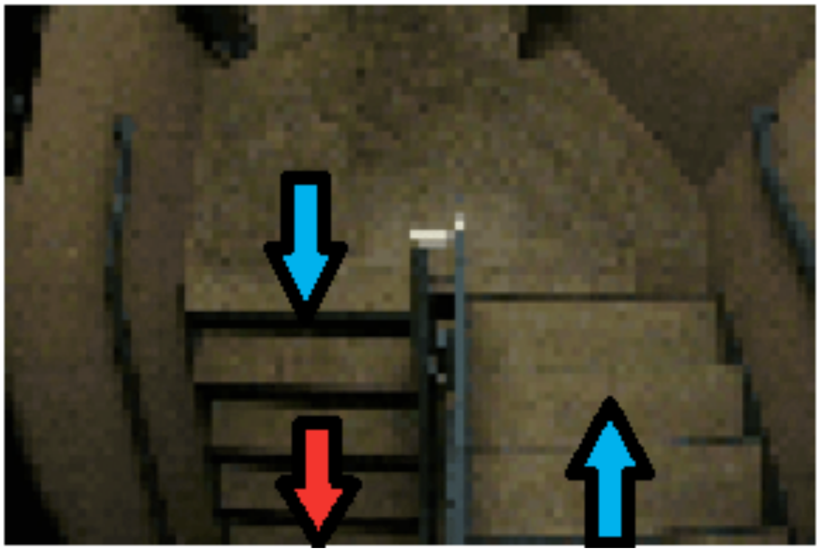


Figure 3: Floor and Stair flows (blue arrows) merge to form one outflow (red arrow).

While not limited to stairwells, transition points would certainly include the stair landings, which are the location of merging events considered in this paper. The effective width is the width of the stairwell or hallway actually used by occupants, and is calculated by subtracting any boundary layer components from the clear width of the space [2]. The boundary layer components are objects such as handrails and benches that detract from the space that the occupant can actually use. From further examination of equation 1, it is clear that the flow in should equal the flow out for any width as long as there is no queue and there are steady state conditions. This will be a main point of comparison for the empirical data presented in this paper. The merging of the stair and floor flows to form the outflow is shown in Figure 3.

Flow rates and velocities of people in stairwells were first examined qualitatively in 1985, where merging of stair and floor occupants was shown to be common in evacuations [3]. In the same year, research by Hukogi et al. [4] included three experiments to examine merging when either the stair flow or floor flow of occupants established itself first. It was found that when either the stair flow or the floor flow established itself first in the merging event, the flow rate into the merging region was split equally between the floor and stairs. When the stair flow and floor flow established themselves at the same time, the flow rate into the merging region favored the floor by about 60% [4].

Pauls reported deference behavior between the flow of people from the stairs and the flow of people from the floor in 2004 [5]. He observed that the stair flow deferred to the floor flow on a fairly consistent basis. Furthermore, Pauls reported that this deference behavior impedes the flow of people from higher floors and can cause complete stoppages of the stair flow [5].

Research by Takeichi et al. in 2006 focused on the floor-stair interface geometry. The authors found that when the door connecting the floor to the landing is located adjacent to the incoming stair, the flow rate of people from the floor increased to be greater then incoming stair flow [6]. Figure 3 illustrates the merging of these flows.

In 2008, Galea et al. concluded that merging behavior at the floor-stair interface greatly affects the speed at which a floor of occupants can be emptied, and that the physical geometry of the floor-stair interface affected this behavior [7]. One interface geometry studied by Galea et al. is shown in Figure 4. They found that when the floor is connected to the adjacent floor entrance, the speed at which a floor can empty improves by up to 58%. Such a finding is in agreement with those of Takeichi et al. and Pauls, however, this improvement negatively impacts the stair flow rate, as Galea et al. reported that the flow rate of people descending from higher floors decreases by up to 55%. Thus, they concluded that the overall building evacuation time is negligibly impacted by the location of the floor connection, but the evacuation times for upper floors were increased significantly. Therefore, Galea et al. recommended that the floor should be connected to the opposite floor entrance [7].

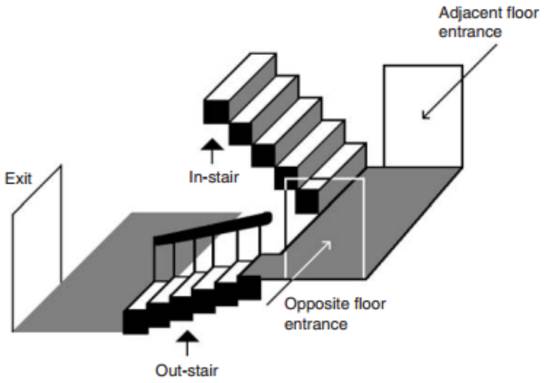


Figure 4: Geometry of a Generic Floor-Stair Interface [7].

Work by the same authors focused on evacuation behavior in the World Trade Center towers on September 11, 2001. Galea et al. used the buildingEXODUS software package to model the evacuation of the north tower. The authors defined a parameter to measure the efficiency at which occupants navigate the congestion on each floor landing. This parameter compared the average amount of time lost by floor occupants due to congestion as a fraction of their average evacuation time [8]. Galea et al showed that this efficiency decreased on higher floors in the building and that the loss of efficiency due to height increased with building population [8].

In 2011, Boyce et al. examined the merging process in three different floor-stair geometries [9]. The authors introduced a methodology for calculating the flow rates in which video cameras were placed inside the stairwell and recorded occupants moving through the merging region. An imaginary line was placed at the stair landing perpendicular to the direction of movement in the stair. When occupants from either the stair or floor flow crossed this line, they were considered to have merged into one flow. The evacuation videos were analyzed to determine how many people merged in a given time period, and to determine whether any bias for the floor or stair flow could be found. Two of the buildings analyzed were university buildings; the floor-stair geometries are shown in Figure 5 and Figure 6.

In both buildings, despite differing geometries, the overall merging ratio was split 50:50 between the stair and floor flows. In Building 1, the merge ratios fluctuated greatly through the course of the evacuation, ranging from 69:31 in favor of the stairs to 30:70 in favor of the floor flow. Despite the varying merge ratios during the evacuation, the overall merge ratio for the building was nearly 50:50.

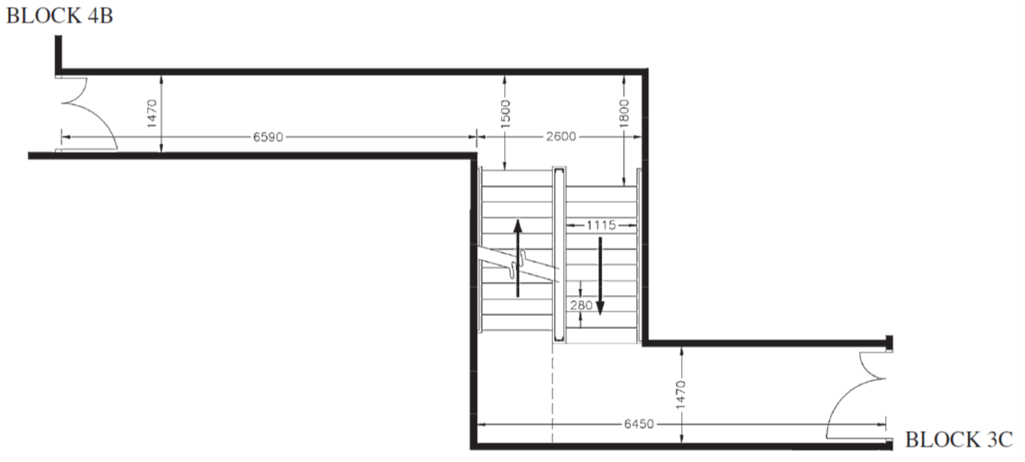


Figure 5: Floor-Stair Geometry for Building 1 [9].

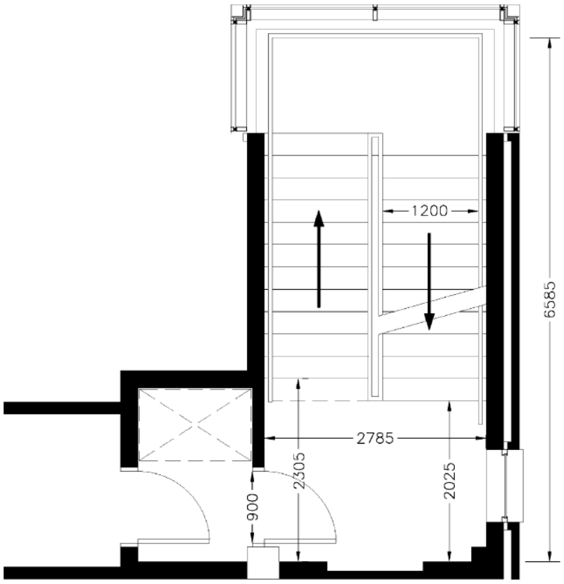


Figure 6: Floor-Stair Geometry for Building 2 [9].

In Building 2, the authors reported little variation in merging ratios over time, and they stated that this was due to the entrance door being located opposite the incoming stair [9]. This work by Boyce, and the previously cited literature all focused on comparing the floor and stair flows to each other. The focus will now shift to comparing the inflow (both the stair and floor flow) to the outflow.

The most recent work on merging was done by Andrew Leahy in his master's thesis [1]. First, Leahy examined incoming and outgoing flow rates of building occupants entering a stair landing with no merging, meaning that there was one flow of incoming occupants either from the stair or from the floor. It was found that the flow rate of people entering the landing was approximately equal to the flow rate of people exiting the landing. Leahy then did the same analysis with occupants merging from the stair and floor flows, and found that outflow was not equal to the sum of the inflows, but rather approximately 60% of the sum of the inflows. Thus, he concluded that merging events do not follow the hydraulic model presented in [2]. Although this statement was made, no explanation for the deviation from the hydraulic model was given. Additionally, Leahy reported that the majority of merging events occur in what he termed the "outside lane” of the stairwell. If one were to divide the stairwell into two imaginary lanes, the majority of merges occur in the lanes closest to the outside wall of the stair.

With this in mind, one can consider then the geometry in Figure 4, with an opposite floor entrance being used. If the floor flow occupants use the outer stair lane and the stair flow occupants use the inner stair lane, it is expected that the merging event should be 100% efficient if all occupants stay in their respective lanes and no queuing occurs.

2.2 TRANSPORTATION LITERATURE

Literature from the transportation field is cited because of the similarities of automobile movement on highways to occupant movement during egress. Both pedestrian and automobile traffic encompass merging flows that can affect behavior both before and after a merging event. Thus, trends in either of these fields may provide insights for a study of occupant movement during egress.

In 1997, Hall and Tsao [10] concluded that uncontrolled merging of vehicles on a highway could result in drastic decreases in flow, on the range of 50-70%. The authors present three different types of merging concepts: autonomous individual merging, cooperative individual merging, and cooperative platooning merging. Autonomous individual merging considers scenarios where the merging vehicles have no communication and follow normal traffic rules. Cooperative individual merging considers scenarios when the merging vehicles are able to communicate electronically through a vehicle-to-vehicle communication system that was studied in the paper. Cooperative platooning is the same scenario with groups of cars merging at the same time. All of these concepts have a relevant analog in occupant merging behavior: single occupants can merge together with or without communication with each other, as can groups or platoons of occupants. The authors found that the reduction in car outflow was over 50% for autonomous individual merging, 25-30% for cooperative individual merging and between 35-70% for cooperative platooning merging [10].

Work by Cassidy et al. in 1999 [11] noted that average rate of vehicle discharge from a queue can be 10% lower than the flow measured prior to queue forming. Concerning the period of time before queuing, the authors comment that, "The onset of upstream queuing was always accompanied by an especially low discharge flow followed by a recovery rate and these are the effects of driver behavior we do not yet understand" [11]. Though this paper does not examine queued occupant behavior, the period of time just before queuing is studied closely [10], thus it is important to note that the onset of queuing is accompanied by low discharge flow rates. Such a finding confirms the logical notion that queuing occurs when the inflow is greater than the outflow.

Work by Cassidy et al. in 2002 [12] examined transit times and flow rates of cars merging onto a three-lane highway. The authors measured the flow rate of cars merging onto the highway, and also the transit time of cars from the on-ramp to a selected point down the road. It was reported that the high flow rates of cars entering the highway caused increased transit times to the point of queues forming. However, the increased transit time was present in the period of time just prior to the formation of any queues, indicating that non-queued merging results in an increased transit time, as well. The authors also reported lower transit times were generally accompanied by higher flow rates leaving the merging event [12].

In 2004, Laval studied the impacts of vehicle accelerations in traffic theory [13]. The author suggested that vehicles accelerating during a lane change maneuver create a flow rate capacity loss. Essentially, as vehicles change speed and direction during lane changes, the overall flow capacity of the road is diminished. Such an observation is important because it indicates that lane changing maneuvers may actually be the cause of merging bottlenecks. Furthermore, it allows a comparison between the bottleneck discharge rate and the overall speed traffic [13].

The conclusions made in the above transportation literature regarding flow, transit time and queuing cannot be replicated for their analogous parameters in human egress behavior without further investigation. Movement of cars and movement of people, are similar, but they are not the same thing. Cars cannot bump into each other while merging, but humans can. Cars cannot readily communicate their intentions beyond a turn signal or brake light, but humans can. It is useful to examine automobile transportation phenomena in order to look for similarities in human egress behavior, but it must be understood that these are two different fields of study.

Nonetheless, the above conclusions provide some trends to look for when analyzing human merging behavior. First, the flow rate may be decreased during merging events by 50% or more, and this decreased flow rate could indicate the onset of a queue. Second, it is expected that high flow rates into a merging event will increase the transit time for occupants to reach a set point after the merger. Finally, occupants changing lanes within the stairwell may decrease the flow rate in the stairwell.

2.3 COMPUTER MODELS

As mentioned previously, the principal goal of this research is to improve computer evacuation models through the study of experimental evacuation data. There are a plethora of evacuation models available, ranging from first order approaches such as the hydraulic model to complicated algorithms that account for various human and environmental factors. A thorough overview of computer evacuation models was conducted in 2005 [14]. The focus of this study will be the advanced evacuation models that provide the most sophisticated simulations of human behavior during building evacuations.

From a review of [14], it is clear that available egress models take a wide variety of approaches to model human behavior. As technology has advanced, models have advanced from dictating occupant behavior with user-defined inputs to replicating human decision-making during egress. The authors of [14] define three different types of egress modeling methods: behavioral, partial behavioral and movement. Behavioral models are defined as, "those models that incorporate occupants performing actions, in addition to movement toward a specified goal (exit). These models can also incorporate decision-making by occupants and/or actions that are performed due to conditions in the building." Partial behavioral models are defined as, "those models that primarily calculate occupant movement, but begin to simulate behaviors. Possible behaviors could be implicitly represented by pre- movement time distributions among the occupants, unique occupant characteristics, overtaking behavior, and the introduction of smoke or smoke effects to the occupant. These are models capable of simulating an entire building, and occupants' movements throughout the model are based on observed human behavior data." Movement models are defined as, "those models that move occupants from one point in the building to another (usually the exit or a position of safety). These models are key in showing congestion areas, queuing, or bottlenecks within the simulated building [14].”

This review will focus on behavioral models only. Again, the empirical data collected and presented here will not be used to simply feed an evacuation model numbers to calculate, as is the case in partial behavioral models. Rather, the data will be used to better understand human merging behavior during evacuation from high rise buildings, which will allow model developers to design better models based on that understanding. Engineers and model developers can then test their human merging algorithms and models against the empirical data to verify that the model accurately replicates human behavior.

2.3.1 BUILDINGEXODUS

The Exodus model was developed by the Fire Safety Engineering Group at the University of Greenwich. Exodus models occupant movement through a fine network of nodes, where each node represents the smallest amount of free space that can be occupied. The movement of each occupant is governed by a set of rules that seeks to model human behavior; these rules have been broken up into the following sub-models: occupant, movement, behavior, toxicity, and hazard. Within the behavior sub-model, Exodus uses parameters called drive and patience that control occupant behavior during conflicts and queuing. These parameters are also affected by the occupant sub-model, which governs characteristics of the occupant such as age, gender, disability, and movement capabilities [7].

When two occupants attempt to occupy the same node at the same time, Exodus considers the two occupants to be in conflict. The conflict is resolved by comparing both occupants' drive parameter, which is in this case their level of motivation to occupy the node. If one occupant's drive is much higher than the others, then that occupant wins the conflict and will occupy the space. The other occupant will either wait for the desired node to again become available, or potentially change direction to another mode. If the occupants have drive values with 10% of each other, then the winner is chosen randomly [7]. A more detailed explanation of occupant movement in Exodus is given in [8].

2.3.2 PATHFINDER

The Pathfinder model was developed by Thunderhead Engineering, with the most recent edition released in 2011. 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, similar to that presented in [2]. Occupant movement and egress time is governed by a flow model that calculates the time for occupants to travel through doors and corridors. Steering mode uses a set of complex algorithms to determine the occupant path, thus readers are referred to [15] 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 costing 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 costing 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. [15]"

2.3.3 LEGION

Legion is a pedestrian simulation software package developed by Legion International, Ltd. Legion models the movement of people on a two-dimensional continuous vector space. This vector space is continuously updated as occupants move, which allows the movement of one single occupant to be based on the best decision for that occupant, not a general set of rules or heuristics. All occupants are assigned one or more objectives, and the model constantly updates each occupant's movement vector as the simulation progresses.

All occupants in Legion are probabilistically assigned social, physical and behavioral characteristics that are based on empirically collected data. The social characteristics include: occupant type (visitor or a regular to the building), age and gender. The lone physical characteristic is body size and the behavioral characteristics include: memory, adaptability and preferences of personal space, walking speed and acceleration.

Legion handles occupant movement on the principle of least effort. This method seeks to minimize an occupant's dissatisfaction value, which is a function of frustration, inconvenience and effort. The value is also affected by an occupant's individual characteristics, location, and local conditions. The model continuously updates each occupant's movement vector in such a way that minimizes the dissatisfaction value while still moving towards the objective. A merging event between occupants is handled in the same manner: each individual occupant moves in a manner that minimizes the dissatisfaction value while still moving towards the objective. [14].

3. FLOW RATE METHODOLOGY

The method for calculating the flow rates of occupants in stairwells went through many revisions. The initial thought was to simply use the same methodology presented in [1], but it was desired to have a foundational understanding of how flow rates are calculated and not simply use a precedent method. The initial method presented in [1] considers merging in 10-second intervals. The flow rate is calculated as the number of people passing through a certain point divided by the time it takes those people to pass that point. 10 seconds is an arbitrarily selected time period utilized as a means to separate the different merging events between groups of people. The entrance and exit times of the first and last people entering and exiting the stair landing are used to determine the time for the occupants to enter or exit the stair.

Through personal correspondence with [16] and [17], another possible methodology was considered in which the flow rate would be calculated as the number of people passing a certain point minus one divided by the time it takes those people to pass that point. This method considers groups of people, and uses the 10-second interval as a way to break up the groups. This "N-1" method was originally considered because the original method in [1] was deemed to be incorrect for considering groups of occupants. For example, if the incoming flow rate was 1 person per second, and the time interval from 700-710 seconds was considered, the methodology would calculate that 11 people entered the stair in 10 seconds, even though the flow rate was 1 person per second. The "N-1" method eliminates this concern by eliminating one occupant from the equation. Another way to view this method is by comparing it to taking a dose of medicine. If one dose of medicine is taken every four hours starting at noon, then the first three doses would be at 12, 4 and 8 pm. By using the method presented in [1], the rate of taking the medicine, or "flow rate" would be three doses divided by eight hours, or 0.375 doses per hour. Clearly, this is incorrect as the dosage rate is 0.25 doses per hour, equivalent to one dose every four hours. Using the " N-1" method, the flow rate would be two doses every eight hours, equivalent to one dose every four hours. In using the "N-1" method, the first occupant essentially starts the timer for that interval, and the rest of the occupants are counted in calculating the flow rate.

In the analysis, both the incoming floor and stair flow rates, the total inflow rate, and the outflow rate are calculated. The incoming flow rates only considers the group of occupants who enter the stair during the chosen time interval, but the outgoing flow rate considers occupants who exit outside that interval as long as they are part of the group that entered within the interval. To better illustrate this, an example problem is presented.

A group of occupants that enter between the time span of 700-710 seconds of the building evacuation is chosen where several occupants enter a stair landing from both the floor and the above stairs. In Table 1, "F" indicates that the occupant entered from the floor, "S" indicates the occupant entered from the stairs above. The in and out times are in seconds.

Origin	In	Out
F	701	703
S	702	704
F	702	703
S	705	709
S	706	708
F	707	710
S	708	709
S	709	712

Table 1: Sample Flow Rate Data.

With the chosen methodology, the three flow rates are calculated:

$$Floor\ Flow = \frac{N_{floor} - 1}{Time} = \frac{2}{707 - 701} = 0.333\, people/sec$$

$$Stair\ Flow = \frac{N_{stair} - 1}{Time} = \frac{4}{709 - 702} = 0.571\, people/sec$$

$$Inflow = \frac{N_{total} - 1}{Time} = \frac{7}{709 - 701} = 0.875\, people/sec$$

$$Outflow = \frac{N_{total} - 1}{Time} = \frac{7}{712 - 703} = 0.778\, people/sec$$

Where:

N_{floor}= number of people entering from the floor

N_{stair}=number of people entering from the stair

N_{total}=Sum of N_{stair} and N_{floor}

It should be noted that the last occupant exited outside the 700-710 second interval, but because they are part of the group that entered during that interval, their exit time of 712 is still counted in the outflow. Additionally, the inflow rate is not calculated by simply adding the floor and stair flow rates together (though it is comprised of the stair flow rate). Such would not be appropriate give that the stair and floor flow rates are calculated over different time periods. The inflow rate is calculated by considering all of the incoming occupants and then dividing by the time it takes all of those occupants to enter the merging area. This keeps the methodology consistent with that presented in [2]

The final equations used are presented below.

$$Floor\ flow\ rate = \frac{N_{floor} - 1}{Time}$$

$$Stair\ flow\ rate = \frac{N_{stair} - 1}{Time}$$

$$Inflow\ rate = \frac{N_{total} - 1}{Time}$$

$$Out\ flow\ rate = \frac{N_{total} - 1}{Time}$$

The time used for the floor rate is the last floor entrance time subtracted by the earliest floor entrance time. The time used for the stair flow rate is the last stair entrance time subtracted by the earliest stair entrance time. The time used for the inflow rate is the last entrance time subtracted by the early entrance time. The time used for the outflow rate is the latest exit time subtracted by the earliest exit time. Note that, because groups of people are considered, the times for the floor, stair and inflow rates must fall between $t_i \leq t < t_f$., but the times for the outflow rate do not have to.

Where:
t_i = early chosen entrance time
t_f = late chosen entrance time

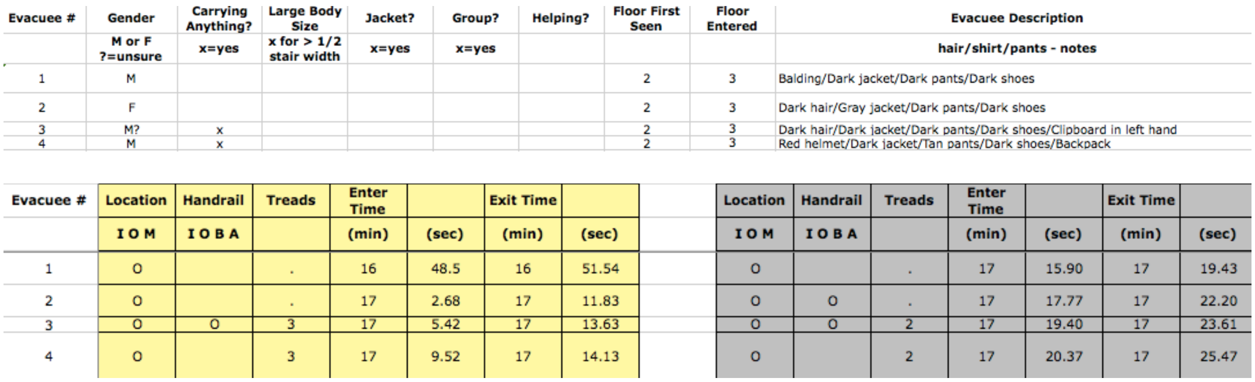
If a period of merging was less than 20 seconds, the period was analyzed as is. If a period of merging was greater than 20 seconds, then it was broken up into 10-second intervals with the last interval generally being greater than 10 seconds. The majority of the chosen time intervals in this paper are 10 seconds long, but some of the intervals are of different lengths.

With the presented flow rate methodology, it is necessary to have at least two floor flow occupants and two stair flow occupants to analyze the merging event. This is because there needs to be both an early and late entrance/exit time for both incoming flows. Merging events that did not meet this requirement were not considered in this analysis. Furthermore, merging events were only considered if a queue of people did not form. This paper seeks to understand human merging behavior in the period of time before queuing occurs. The hydraulic model described in Chapter 2 gives guidelines for calculating flows under several different scenarios. First, if the outflow is greater than the maximum specific flow for the egress component (in this case it is the stairs), then a queue forms. This case is not analyzed in this paper. Second, if the outflow is equal to the maximum specific flow for the egress component, then equation 1 determines how the incoming flows form the outflow. Finally, if the outflow is less then the maximum specific flow for the egress component, there is no way to quantify how the incoming flows form the outflow, it is just known that the outflow is equal to the incoming flows.

These last two cases are considered for the present analysis. Because this paper is examining flows and not predetermining them, equation 1 can be used readily to calculate what the hydraulic model predicts and compare this value to the actual data. The composition of the outflow relative to the inflows does not need to be predicted by a model, as it can be readily seen from the data.

4. NIST BUILDING EVACUATIONS

The quantitative data used for the analysis is located in several spreadsheet files generated by NIST [18]. 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 7 and the figures in the next section. Each occupant's physical appearance was recorded, as well. Thus, an occupant's progress towards the exit can 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 recorded. To supplement this data, the evacuation videos of each stairwell were also examined. 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 #	Gender	Carrying Anything?	Large Body Size	Jacket?	Group?	Helping?	Floor First Seen	Floor Entered	Evacuee Description
	M or F ?=unsure	x=yes	x for > 1/2 stair width	x=yes	x=yes				hair/shirt/pants - notes
1	M						2	3	Balding/Dark jacket/Dark pants/Dark shoes
2	F						2	3	Dark hair/Gray jacket/Dark pants/Dark shoes
3	M?	x					2	3	Dark hair/Dark jacket/Dark pants/Dark shoes/Clipboard in left hand
4	M	x					2	3	Red helmet/Dark jacket/Tan pants/Dark shoes/Backpack

Evacuee #	Location	Handrail	Treads	Enter Time		Exit Time		Location	Handrail	Treads	Enter Time		Exit Time	
	I O M	I O B A		(min)	(sec)	(min)	(sec)	I O M	I O B A		(min)	(sec)	(min)	(sec)
1	O		.	16	48.5	16	51.54	O		.	17	15.90	17	19.43
2	O		.	17	2.68	17	11.83	O	O	.	17	17.77	17	22.20
3	O	O	3	17	5.42	17	13.63	O	O	2	17	19.40	17	23.61
4	O		3	17	9.52	17	14.13	O		2	17	20.37	17	25.47

Figure 7: Sample spreadsheet data.

4.1 DESCRIPTION OF BUILDINGS

In the following sections, a description of each building is given, along with important data about the buildings, such as stair measurements and occupant load. The locations used for the times of occupants entering and exiting the camera are also given. All of the building evacuations were unannounced, meaning none of the occupants were aware of the drill until the alarm sounded. A summary of important building data is displayed in Table 2. The effective width is found by subtracting the boundary layer widths of obstructions such as handrails, as detailed in [2].

Building	Floors	Stair Width (m)	Effective Stair Width (m)	Stair	Number of Occupants
4	24	1.12	0.82	A	249
				B	356
5	10	1.27	0.97	A	436
				B	368
7	18	1.12	0.73	3	292
8	31	1.38	1.08	N	704
				S	538

Table 2: Summary of Important Building Data.

4.1.1 DESCRIPTION OF BUILDING 4

Building 4 is a 24-story office building on the west coast of the United States. The building consists of two stairs, labeled Stair A and Stair B. Both stairs are 1.12 m wide, with a clear width of 1.02 m and the individual steps have a 0.18 m rise and 0.28 m tread depth, all measured by NIST [18].

The evacuation drill observed by NIST took place in the spring of 2008 during normal business hours before lunchtime, and 605 occupants participated in the full building evacuation drill (249 in Stair A and 356 in Stair B). NIST collected data from 23 different camera locations in Stairs A and B. In Stair A, 11 cameras were placed on every other floor beginning at the exit floor (Floor 2) and ending with Floor 22. In Stair B, 12 cameras were placed on every other floor beginning at the exit floor (labeled as P1), and then continuing on every other even floor from Floor 2 to Floor 22. The camera view was of the stair landing and a few steps on either side.

For Building 4, the times of the occupants entering the camera view were taken 2-3 steps away from the main landing (leading to the main landing) and 3-4 stairs away from the main landing (leading away from the main landing). The variation in timing positions was due to the differences in camera views, as some cameras were equipped with wide-angle lenses that could capture a higher number of steps in addition to the main landing. A wider angle view is shown in Figure 8, where the camera view shows 3 steps leading to the main landing and 4 steps leading away from the main landing [18].

Figure 8: Typical Stair Landing of Building 4 [18].

4.1.2 DESCRIPTION OF BUILDING 5

Building 5 is a 10-story office building on the west coast of the United States. The building has two stairs: Stairs A and B, both of which exit directly out of the building. The two stairs are 1.27 m wide with a 1.22 m clear width, and the individual steps have a 0.18 m rise and 0.28 m tread depth, all measured by NIST [18].

The evacuation drill observed by NIST took place in the spring of 2008 during normal business hours before lunchtime, and 804 occupants participated in the full building evacuation drill (436 in Stair A and 368 in Stair B). On the day of the drill, NIST collected data from 10 different camera locations in the two stairs observed. In Stairs A and B, 5 cameras were placed in each stair every other floor beginning at the exit floor (Floor 1) and up to Floor 9. For Building 5, the times of the occupants entering the camera view were taken 3-4 steps away from the main landing (leading to the main landing) and 4-6 stairs away from the main landing (leading away from the main landing). The variation in timing positions was due to the differences in camera views, as some cameras were equipped with wide-angle lenses that could capture a higher number of steps in addition to the main landing. A wider angle view is shown in Figure 9, where the camera view shows 4 steps leading to the main landing and 6 steps leading away from the main landing [18].

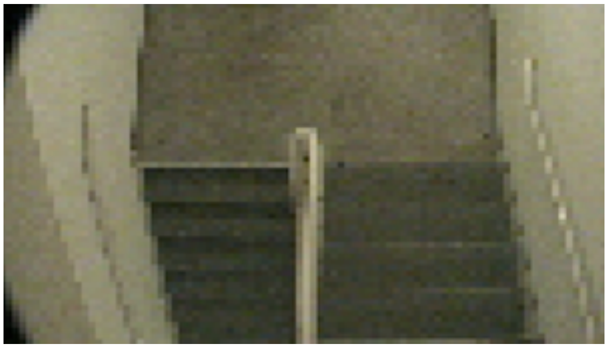


Figure 9: Typical Stair Landing of Building 5 [18].

4.1.3 DESCRIPTION OF BUILDING 7

Building 7 is an 18-story office building housed in three wings, with an adjoining a fourth corridor at one end of the wings. The building houses approximately 4,000 people and has twelve stairs available for egress, numbered one through twelve. NIST observed people movement in four of these stairs; specifically Stairs 1, 3, 7, and 12. Each stair is 1.12 m wide with a 0.91 m clear width, and the individual steps have a 0.19 m rise and 0.25 m tread depth.

Stair 3 exited to the lobby area on the fifth floor each through a 0.91 m wide door [18]. At the writing of this paper, only data for Stair 3 was available.

The evacuation drill observed by NIST took place in the spring of 2008 during normal business hours before lunchtime. Within the four stairs observed, 1,084 occupants participated in the unannounced full building evacuation drill (292 occupants in Stair 3). Also, the local area Community Emergency Response Team (CERT) members stood at the entrance to Stair 2 and relayed to building occupants that Stair 2 was blocked and they needed to find another stair (likely causing a higher number of occupants to use the stairs near Stair 2 (Stairs 1 and 3) than normally expected during an evacuation). In Stair 3, cameras were placed every other floor beginning at the exit floor (Floor 5) and ending with Floor 17. For Building 7, the times the occupants entered the camera view are taken 2 steps away from the main landing (leading to the main landing) and 3 stairs away from the main landing (leading away from the main landing). A typical stair landing of Building 7 is shown in Figure 10 [18].

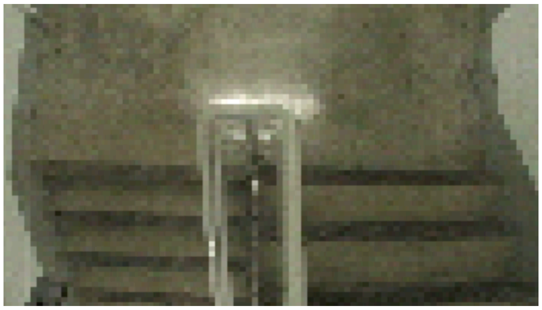


Figure 10: Typical Stair Landing of Building 7 [18].

4.1.4 DESCRIPTION OF BUILDING 8

Building 8 is a 31-story office building on the East Coast of the United States. The building has two stairs (North and South) that both exit on the 2nd floor onto the street level. The two stairs are 1.38 m wide with a 1.26 m clear width, and the individual steps have a 0.18 m rise and 0.27 m tread depth, all measured by NIST [18].

The evacuation drill observed by NIST took place in the fall of 2008 during normal business hours before lunchtime. Overall, 1242 of building occupants participated in this evacuation drill (704 in the North Stair and 538 in the South stair).

On the day of the drill, NIST collected data from 30 different camera locations in the two stairs observed. In both stairs, NIST placed cameras every other floor, specifically on floors 30 to 14 (every other floor), 11, 9, 7, 5, 4, and 2. Cameras were placed on odd floors between floors 11 to 5 because the building did not have a 13th floor. Cameras were also placed on even floors at the base of the stair (floors 2 and 4) since the exit floor (Floor 2) must be equipped with a camera to obtain exit times for all participants. For Building 8, the times of the occupants entering the camera view was taken at the edge of the main landing (shown by the green line in Figure 11) and the times of the occupants leaving the camera view is taken at the edge of the main landing (shown by the red line in Figure 11) [18].

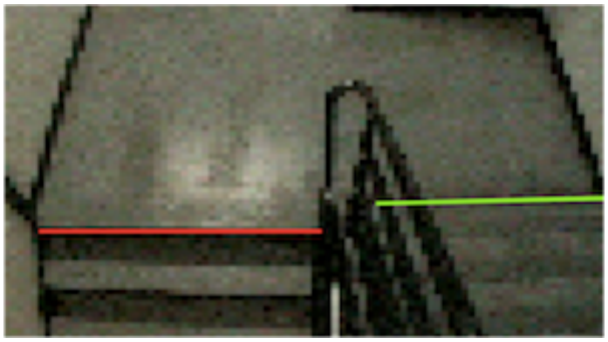


Figure 11: Typical Stair Landing of Building 8 [18].

4.2 FLOW RATE DATA

All 101 merging events that fit the criteria described in the flow rate methodology section were analyzed using the method described in chapter 3. The stair flow, floor flow, inflow and outflow were calculated for each merging interval, as well as the number of occupants in each inflow. Figure 12 shows a view of a stair landing with some sample occupants. The three sample stair occupants, shown in blue, add to the stair flow rate as they cross the blue line. The two sample floor occupants, shown in red, add to the floor flow as they cross the red line. These two flows merge to form the outflow, which is calculated upon crossing the white line.

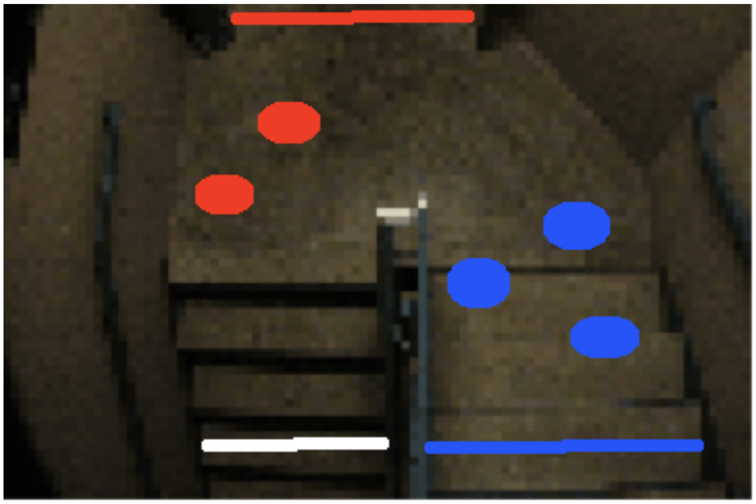


Figure 12: Stair landing shown with sample occupants and flow rate lines.

In most cases, the sum of the inflows was greater than the outflow rate. Because this does not follow the behavior predicted by the hydraulic model [2] and equation 1, the actual outflow was divided by the inflow (the expected outflow) and multiplied by 100 to get the flow ratio. This calculation was done for all merging events and serves as the main parameter for later analysis. The flow ratio for each floor is shown in Table 3, along with the standard deviation. A complete summary of the data for all merging events is given in Appendix 1: Merging Data.

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	102	75.6	23.0

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

Table 3: Merging Data Sorted by Stair.

A distribution of all merging events for all buildings is shown in Figure 13. Analyzing all merging events, the mean percent of expected outflow was 75.6%, with a standard deviation of 23.0. The majority of the events had a flow ratio less than 100, but eight of the events had flow ratios greater then 100, indicating that the outflow was greater then the total inflow.

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[1] Flow ratio and standard deviation are for all merging events.

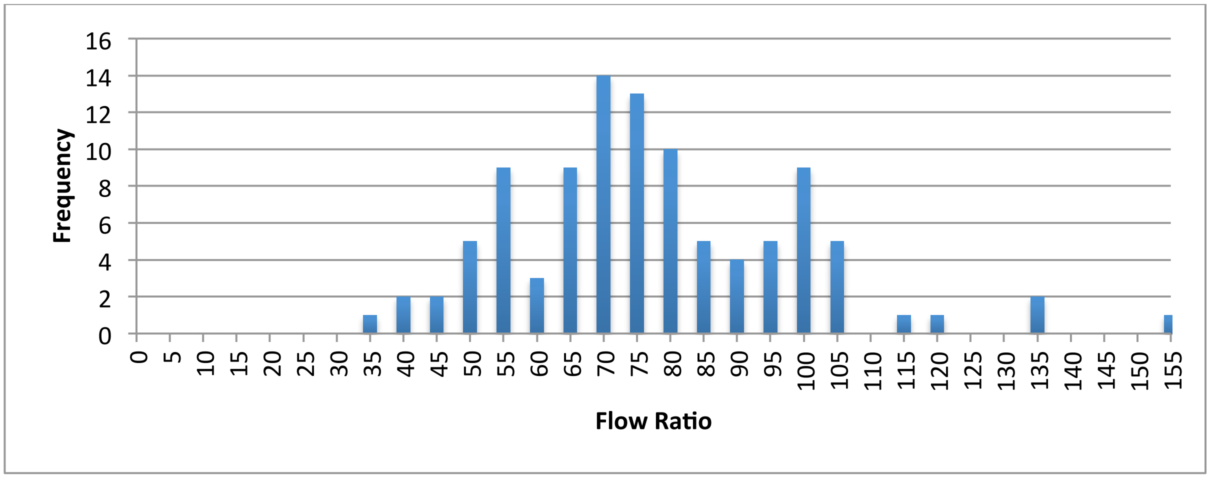

Figure 13: Distribution of Percent of Expected Outflows.

Next, the merging data was compared with various parameters in an attempt to correlate the merging efficiency. First, the flow ratio was examined as a function of stair width, as shown in Figure 14. It seems that the flow ratio is somewhat proportional to stair width, although the trend is not strong as indicated by the low R^2 value in Figure 14.

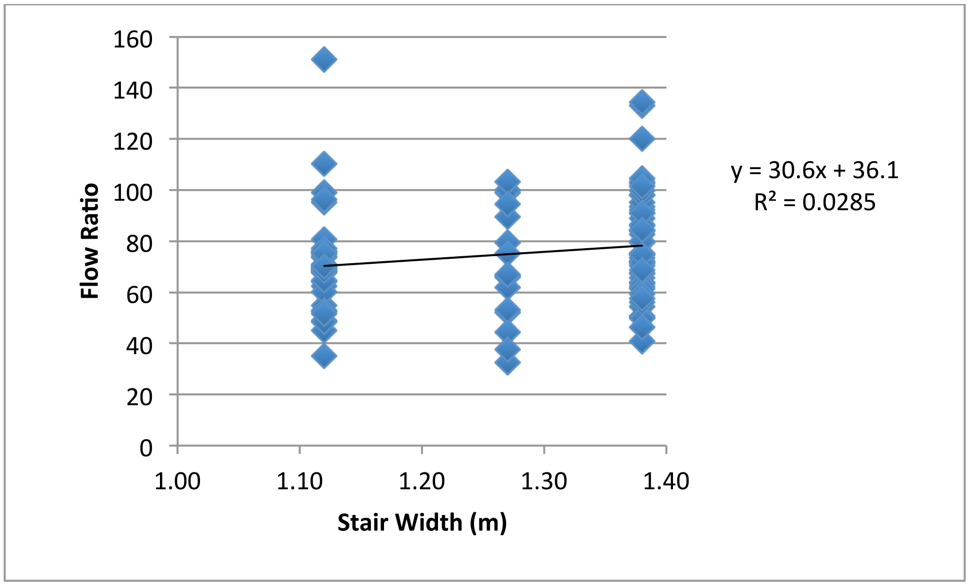

Figure 14: Flow Ratio vs. Stair Width.

The results of the comparison of the flow ratio to the inflow rate are shown in Figure 15. The flow ratio is inversely proportional to the inflow rate, i.e. the higher the inflow the lower the flow ratio. The flow ratio as a function of the stair flow and the floor flow is shown in Figure 16 and Figure 17, respectively. From these figures, there seems to be no trend in the relationship between the flow ratio and the stair or floor flows. This is shown by the R^2 values being less then .013, indicating the data fits the given trend line very poorly.

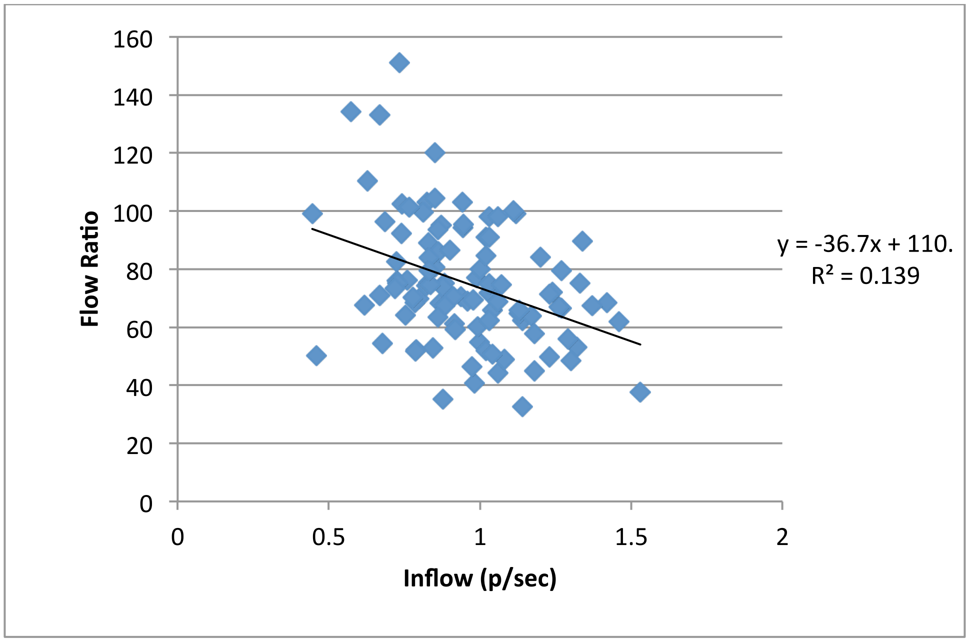

Figure 15: Flow Ratio vs. Inflow Rate.

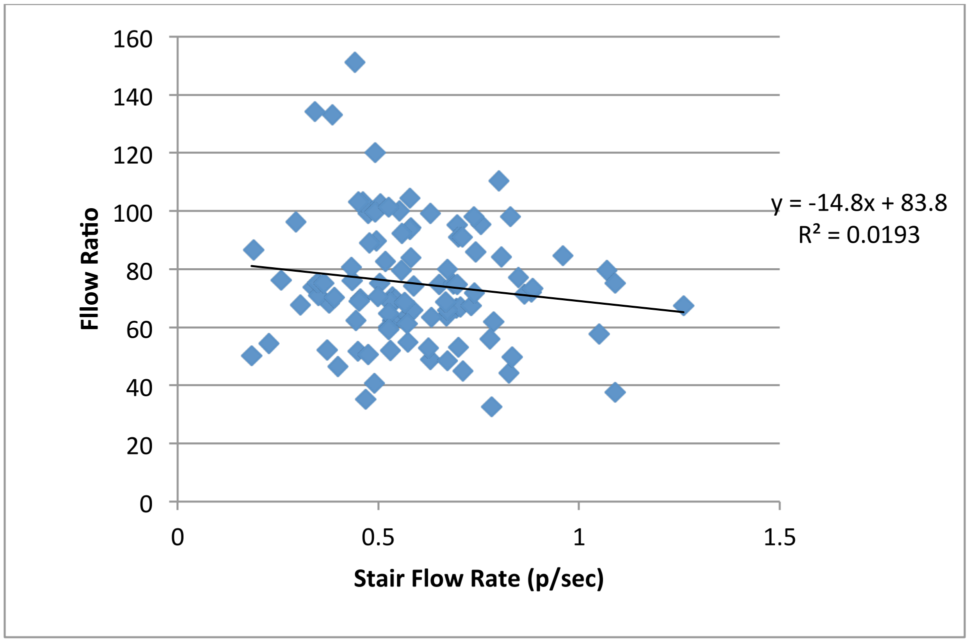

Figure 16: Flow Ratio vs. Stair Flow Rate.

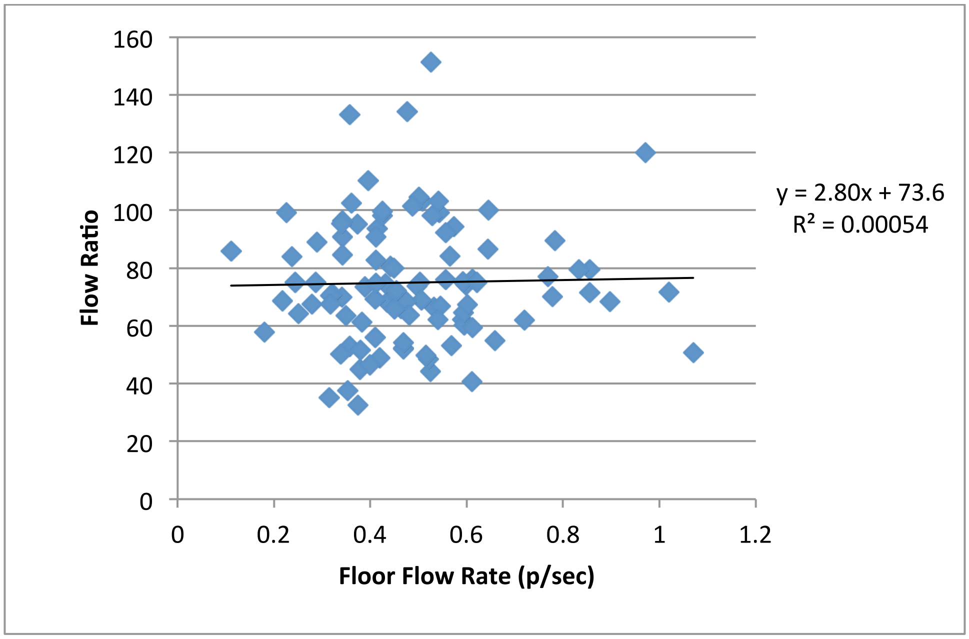

Figure 17: Flow Ratio vs. Floor Flow Rate.

The flow ratio is compared to the actual outflow rate, as shown in Figure 18. There is a clear trend in the data indicating that the outflow rate is proportional to the percent of the expected outflow. The relatively high R^2 value confirms this. Because of the varying stair widths, this comparison is also shown as a function of the specific outflow rate in Figure 19. The specific outflow is the outflow rate divided by the effective width of the stair. Normalizing the outflow in this manner yields a trend line with a smaller slope and also lowers the R^2 value. The maximum specific flow of 1.15 p/s-m noted in [2] is also shown in Figure 19.

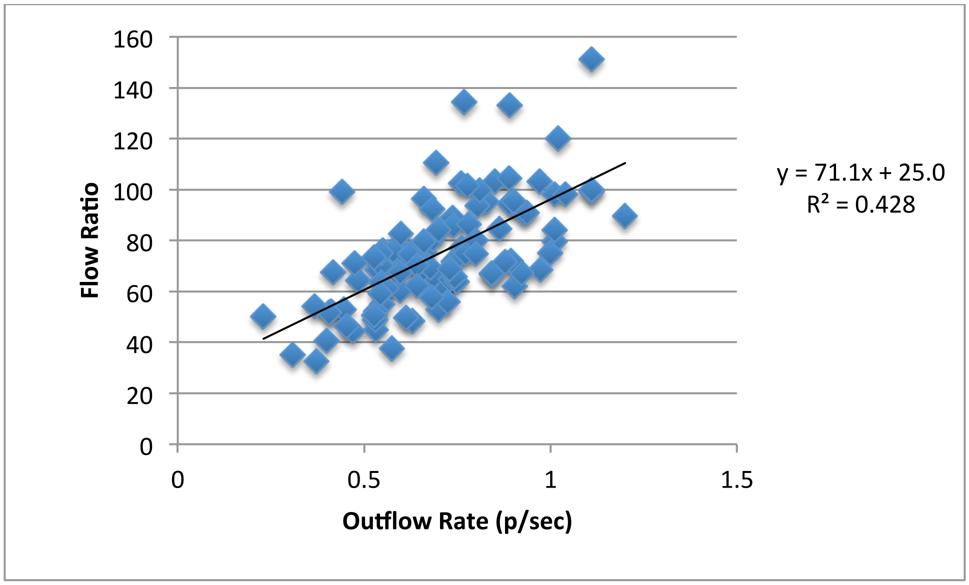

Figure 18: Flow Ratio vs. Outflow Rate.

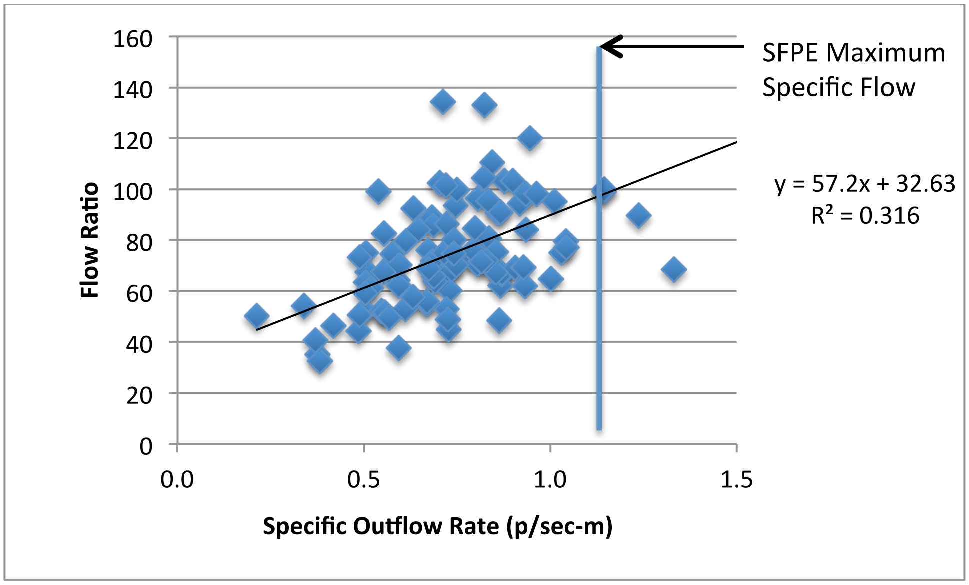

Figure 19: Flow Ratio vs. Specific Outflow Rate.

Finally, the percent of the expected outflow was compared to the floor number, as shown in Figure 20. Due to the varying heights of the buildings used, there were more data points on the lower floors then the upper floors. Nevertheless, there seems to be no correlation between the percent of the expected outflow and the floor in the building, as indicated by the low R^2 of 0.02.

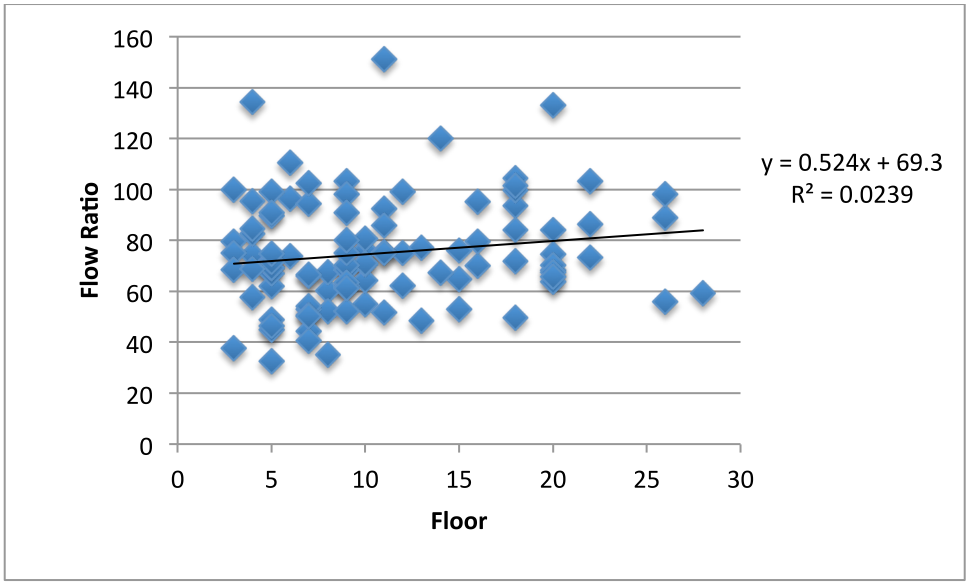

Figure 20: Flow Ratio vs. Floor Number.

4.3 FLOW RATE DATA ANALYSIS

Given that the actual outflow was on average 75% of the inflow rate, the data presented in this paper qualitatively agrees with the findings of [1] that merging events in stairwells do not follow the hydraulic model presented in [2]. The data from this paper includes some of the same data analyzed by Leahy, but the methodology used for the analysis was different, as described in Chapter 3. Quantitatively, the expected outflow rates presented here are higher than the approximately 60% presented by Leahy, but this is still within one standard deviation of the present data.

From Figure 14, there seems to be a slight correlation between the flow ratio and stair width. Logically, this seems to make sense, as the wider a passageway, the more people should be able to pass through that passageway in a given amount of time. However, the data is highly fluctuating as shown by the low R^2 value in Figure 14. This indicates that increasing the width of stairwells will not definitively improve the efficiency of merging events, at least not in the range of stair widths considered in this study.

From examination of Figure 15, it is clear that as the inflow rate to merging events increases, the efficiency of the mergers decreases. This finding is in disagreement with the hydraulic model, which states that the inflow rate to a merging event should equal the outflow rate, assuming no queue forms. In terms of the conservation of people, it does not make sense that the flow rate decreases through the merging event. If the merging event is considered as a control volume, then the flow of people in should equal the flow of people out plus any “storage” of people in the landing. However, the flow rate methodology counts all occupants as they enter and exit the landing, thus no people are actually “stored” on the landing, though there is clearly a change in flow on the landing. It is important to remember that this data for each event is only representative of a 10-second period of time. If this behavior continued over an extended period of time, this behavior would lead to a queue forming. As occupant enter the landing faster then they leave for an extended time, the number of occupants on the landing would increase, which would eventually lead to a queue. Nevertheless, the loss of flow rate during the merging must be accounted for somewhere.

Despite the fact that the inflow is comprised of the stair and floor flows, this same trend is not seen when the individual flows are compared to the flow ratio. As shown in Figure 16 and Figure 17, there seems to be no correlation between the flow ratio and the stair and floor flows. It is unclear as to why this is the case, though it is apparent that the total inflow is what affects the merging efficiency.

This same issue is examined from the opposite end in Figure 18, which shows that the flow ratio is directly proportional to the actual outflow rate. Given that the flow ratio is the percent of expected outflow per the hydraulic model, this trend makes sense. As the actual outflow rate increases, it gets closer and closer to its expected value. The linear trend line fitted to the data in Figure 18 has the lowest error of any trend in this section with an R^2 value of 0.47. Such a value is high for data dealing with human behavior and human movement, indicating that there is appreciable confidence that the indicated trend exists. A similar result was found when examining the specific outflow rate, as shown in Figure 19. The flow ratio is still directly proportional to the specific outflow, though the data is somewhat more scattered from the fitted trend line. The reason for this is unknown.

The final comparison made was between the percent of the expected outflow and the floor level, as shown in Figure 20. As indicated previously, there seems to be no correlation between these two parameters.

Merging events with a flow ratio greater than one standard deviation of the average flow ratio (75 ± 23%) were analyzed for any distinct characteristics that could explain their large deviation from the mean. Two major trends were found. First, all merging events with a flow ratio greater than 100% were found to have an inflow rate less than one person per second. Second, all merging events with a flow ratio less than 50% were found to have an outflow of less than 0.75 people per second. Clearly, the first trend indicates that the occupants entered the landing camera view at a slow rate and then increased their flow rate before exiting the camera view while the second trend indicates that occupants entered the landing camera view at a fast rate then decreased their flow rate before exiting the camera view.

From viewing the NIST evacuation videotapes, it is clear that the merging events caused hesitation by the occupants. While there was some hesitation due to occupants interacting with other occupants in their flow (e.g. floor occupants hesitating behind other floor occupants), there was significantly more hesitation when occupants encountered other flows. Qualitatively, this hesitation itself appears to be a contributor to the decrease in flow ratio. This noted hesitation likely resulted in a decreased outflow rate and velocity of the occupants, as well as an increase in the time necessary to travel through the camera view. Quantitatively, it is difficult to measure hesitation. One method of doing so, which is presented in the next chapter, is to measure the time it takes occupants to travel through the camera view. An increase in this time during merging events would indicate that the occupant hesitated during the merger. This method gives one way to quantify occupant hesitation, though other methods such as measuring change in velocity or density are possible for future study.

This hesitation was clearly seen in the videos for the outlying cases described above. In the merging events where the flow ratio was less than 50%, occupants consistently hesitated when encountering another flow of occupants. This hesitation was seen in a visual decrease in speed and in some cases, a momentary pause in movement during the merger. An attempt to quantify this hesitation is given in Chapter 5. For the merging events where the flow ratio was greater than 100%, a visual increase in occupant speed was clearly seen on the stairwell landing. Besides the correlation between the inflow and outflow rates, no other explanation for the events with outlying flow ratios was found.

The final analysis conducted was comparing the flow ratio to the number of people present in each merging event. The number of floor and stair occupants in each event is given in Appendix 1: Merging Data. No correlation was found between these parameters.

In summary, it is observed that merging events do not precisely follow the hydraulic model and that on average the outflow is 75% of the inflow (which is the expected outflow if no queue forms). This inefficiency seems to have some correlation to the stair width and both the inflow and outflows themselves. However, the question still remains: why does this merging inefficiency exist? The above correlations provide insights about the inefficiency, but they do not explain the cause of it.

4.4 TRANSIT TIME DATA

Next, the cause of the merging inefficiency and the observed occupant hesitation was explored by measuring occupant transit times on landings. The building egress data was analyzed to determine the transit time for occupants to pass through the camera view. Nominally, this is the time it takes the occupant to navigate the landing plus a few steps on either side. The transit time was calculated by subtracting the occupants entrance time from the exit time. To compare the effects of merging, transit times were calculated for occupants on each floor before and during each merging event. Essentially, the occupants' transit time during merging was compared to a baseline occupant transit time under normal, non-merging conditions. These two times were then compared by parameters called the stair and floor ratios. The stair ratio is the average transit time before each merging event divided by the average transit time during each merging event for stair occupants. A summary of the results is shown in Table 4. The floor ratio is the same but with the floor transit times. Stairs that had no occupants pass through the landing before a merging event began were not included in this analysis. The complete set of transit time data is given in

Appendix 2: Transit Time Data.

Stair	Stair Ratio	Floor Ratio
4A	0.44	0.75
4B	1.10	0.84
5A	0.66	0.67
5B	0.60	0.54
7_3	0.69	0.65
8N	0.62	0.72
8S	0.82	0.80
Total[2]	0.67	0.70

Table 4: Summary of Transit Time Ratios.

As shown in in Table 4, the merger transit time was on average 67% of the normal transit time for stair occupants and 70% of the normal transit time for floor occupants. An example of the stair, floor and flow ratio for each event for stairwell 5A is shown in Figure 21. Corresponding figures for each stair are given in

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[2] Total stair and floor ratio are for all merging events.

Appendix 2: Transit Time Data. The flow ratio is individually compared to the stair and floor ratios in Figure 22 and Figure 23, respectively.

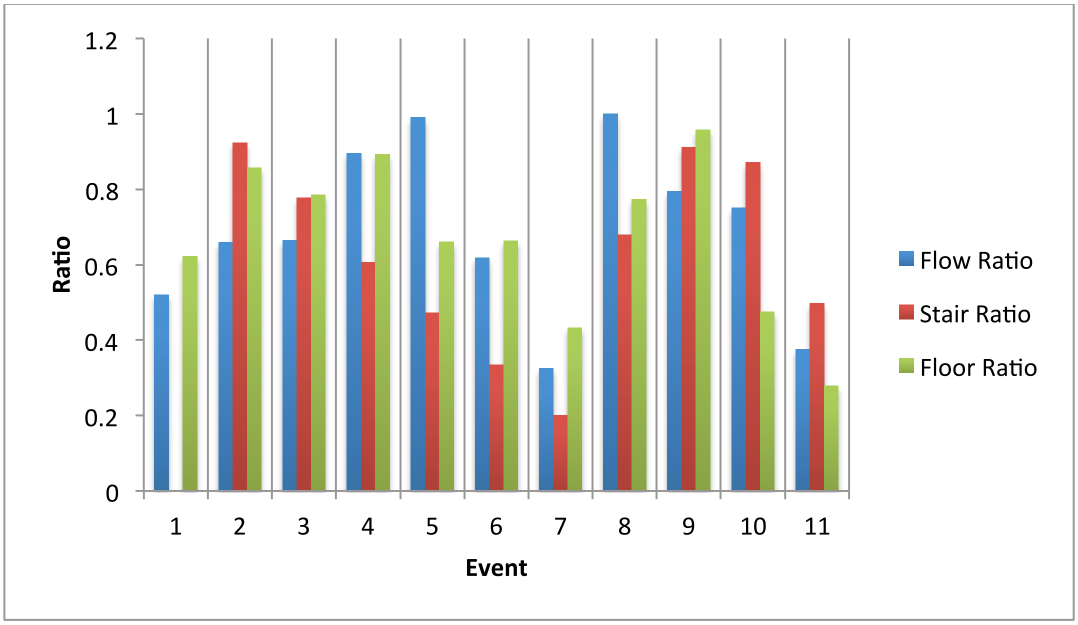

Figure 21: Flow, Stair and Floor Ratios for Stairwell 5A.

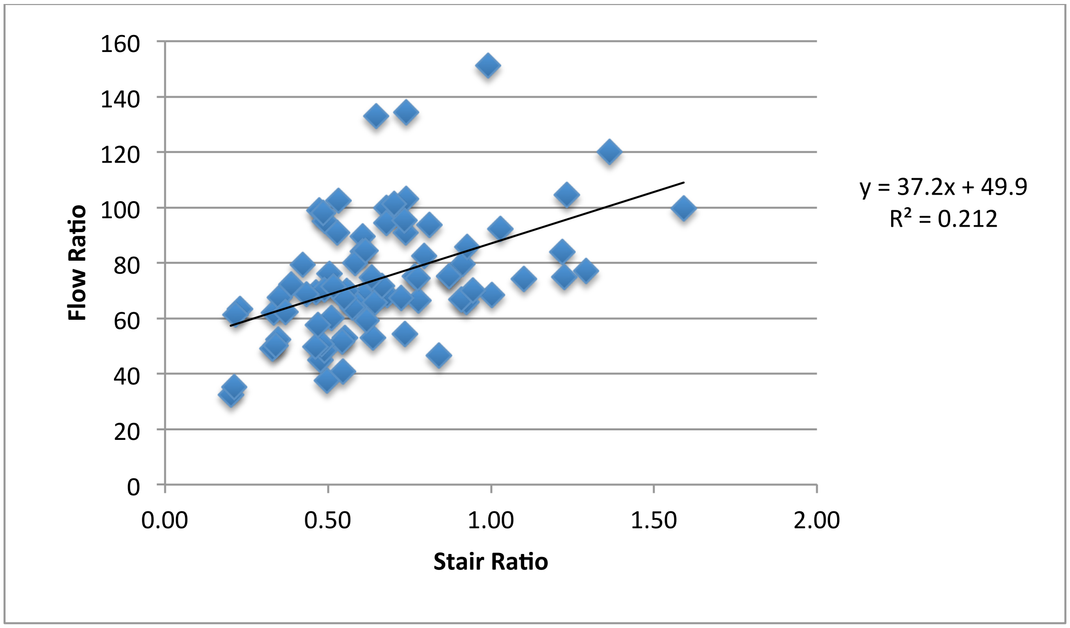

Figure 22: Flow Ratio compared to the Stair Ratio.

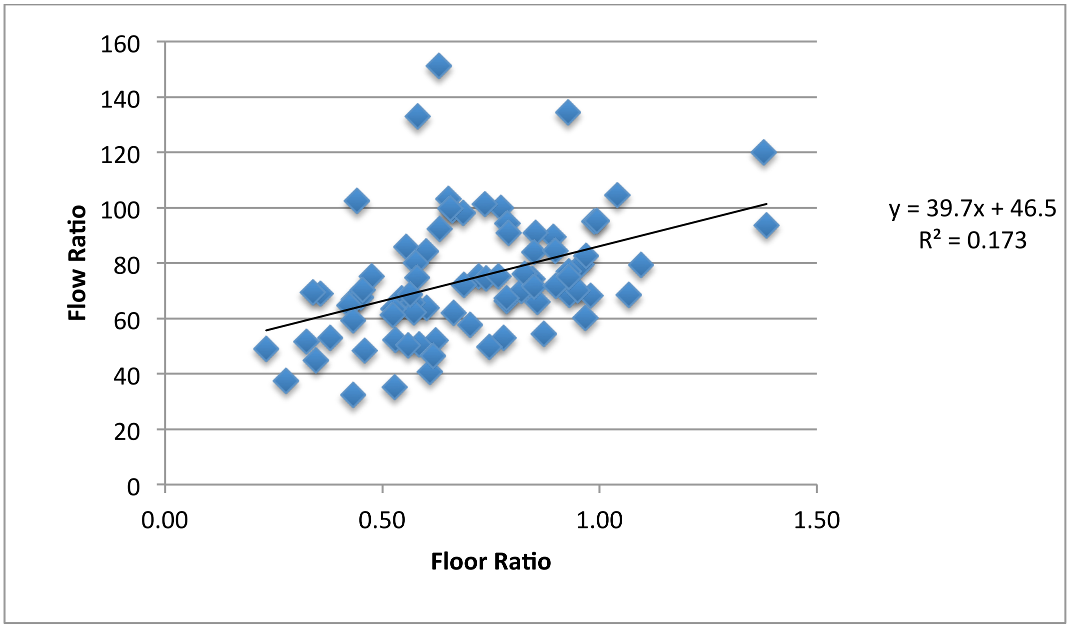

Figure 23: Flow Ratio compared to the Floor Ratio.

The average change in transit times for both floor and stair occupants are shown in Table 5. These times are the average absolute change in transit times, with the positive number indicating that the merge transit time is larger than the normal transit time.

Stair	Stair Change	Floor Change
4A	5.82	1.65
4B	3.38	0.36
5A	3.41	2.76
5B	4.63	3.50
7_3	3.51	3.28
8N	3.13	1.84
8S	1.08	1.01
Total[3]	3.35	2.12

Table 5: Change in Transit Times (sec).

4.5 TRANSIT TIME ANALYSIS

The data in Table 4 gives a macroscopic picture of the effect that merging has on transit times. The normal transit time is on average 67% of the transit time during merging events for stair occupants. A similar number of 70% is shown for floor occupants. These averages are comparable to the flow ratio, which is on average 75%. This similarity could be due to a number of explanations. First, the decrease in flow rate during merging events could be dependent on the increase in transit times. Second, the increase in transit times could be dependent on the decrease in flow rates. Third, these two changes could be interdependent. Before one of these explanations is chosen, further analysis of the data must be made.

Next, the data in Table 5 indicates that on average there is an increase in transit time of 3.35 seconds for stair occupants and 2.12 seconds for floor occupants. Apart from relating this to the

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[3] Total stair and floor change for all merging events.

flow ratio, it is a significant finding that non-queued merging results in an increase in transit time. It makes sense that the average stair transit time increases more, as these occupants have a further distance to travel and thus more room for the merging event to slow them down. This difference in travel distances is shown in Figure 24.

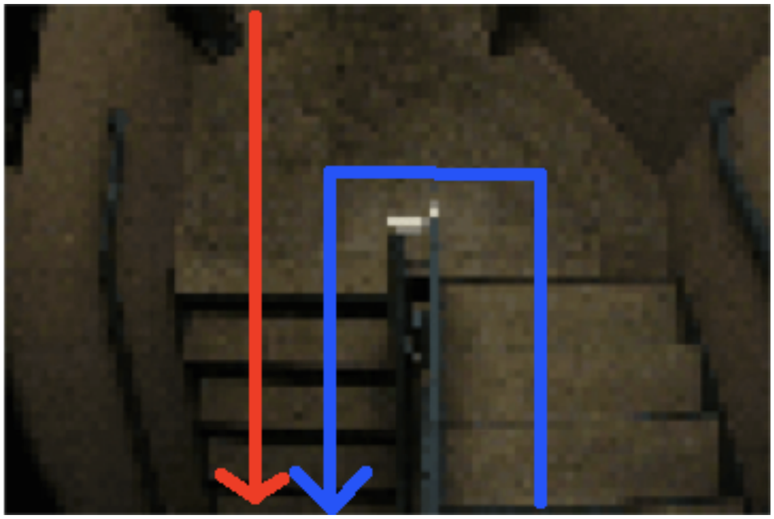


Figure 24: A sample landing view showing difference in travel distances for stair (blue line) occupants and floor (red line) occupants.

From the data given in Figure 21, Figure 22, Figure 23 and

Appendix 2: Transit Time Data, it is appears that no strong conclusions can be drawn between the flow ratio and transit time ratios for individual merging events. Fluctuating behavior from event to event was also seen in [7]. However, some general observations can be made. The data shows that when the flow ratio is less than one, the transit time ratios are generally also less than one. Additionally, very low flow ratios are not accompanied by very high transit time ratios, and vise versa. The flow ratio is directly proportional to both the floor and stair ratios, as shown by the positive slope of the trend line in Figure 22 and Figure 23. This makes sense, as a lower flow ratio should be accompanied by a higher transit time, which is indicated by the higher floor and stair ratios in the figures. The transit time ratios and flow ratios seem to be related on the large scale, but there is a high amount of variation between the two numbers on the small scale. These noted trends from the data agree with the observed occupant behavior from the videotapes. With the observed hesitation during the merging of the stair and floor flows, it makes sense that occupant transit times increased during merging. Hesitation is accompanied by a decrease in velocity, which therefore increases the landing transit time.

From comparing the flow ratio to the stair and floor ratios, there seems to be no evidence that any one of the parameters causes the other. It is most likely that these parameters are interdependent, in that one cannot be present without the other. The decrease in flow during the merging events necessitates a decrease in the transit time. From the flow rate methodology explained previously, all occupants that enter the camera view in the designated time period are also counted as part of the outflow during that time period, regardless of how long it takes them to exit the camera view. Thus, the methodology counts all people in the designated time. If the number of people counted does not change between the inflow and outflow, then the decreased flow rate must be caused by the increase in the time it takes for the occupants to leave the camera view (In other words, if a fractional number decreases and it is known that the numerator remains constant, then the denominator must increase. Because it is known that the flow ratio decreases and the number of people remain constant, the time in the denominator must have increased). While this time in the denominator is not the individual transit time of any occupant, it is the overall transit time for the group of occupants. Thus an increase in this time value in the denominator would indicate that the average transit time for individual occupants has increased.

Because of this, the only definite conclusion that can be made is that merging causes a decrease in the flow, stair and floor ratios, and that these changes are present simultaneously. This means that the transit times for floor and stair occupants during merging events are greater than under normal circumstances, and similarly the outflow of occupants during merging events is less than expected.

5. PATHFINDER EVACUATION MODELING

After review of the three computer egress models presented in Chapter 3, one model, Pathfinder 2011 was chosen for use in this paper. Just one model was chosen because all three of the presented models are behavioral models that attempt to replicate occupant decision-making, and a comparison of all existing models is outside the scope of this work. Rather, Pathfinder 2011 will be used in this study to compare the empirical data to one existing model. This comparison will show how accurately the model replicates human merging behavior, specifically the inefficiency that exists in mergers. The comparison should show the magnitude of this inefficiency, if it does exists, as well as any parameters that may affect it. Pathfinder 2011 was chosen because: 1. Its steering mode is clearly and accurately documented for analysis of how it models human decision-making. 2. Its SFPE mode makes comparison between the hydraulic model and a behavioral model easy. 3. It is widely available in the consulting engineering field due to its low cost. After analyzing the empirical data from the NIST evacuations, a similar analysis was begun using the Pathfinder 2011 computer modeling software.

A sample geometry was constructed as an example in Pathfinder to replicate merging events from the NIST data. The stair was constructed using the dimensions of the stairs in Building 5. A picture of the geometry is shown in Figure 25. Two rooms were added to the geometry, which was filled with occupants for each situation. One room provided the source of people for the stair flow and the other provided people for the floor flow, and a random number of 2-7 occupants were 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 any queuing from occurring. 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. The number of trials was set at 20 in order to simulate the range of possible inflows (between 4 and 14 people total in this case) without going to the extreme of simulating all possible permutations of floor and stair occupants. For each trial, the simulation was run twice: once in the SFPE mode and again in the steering mode. All other parameters remained constant between the two simulations of each trial, including the position of the occupants. Generally, the model inputs were set to their default settings, but a full listing of the input parameters can be found in Appendix 3: Pathfinder Merging Behavior.

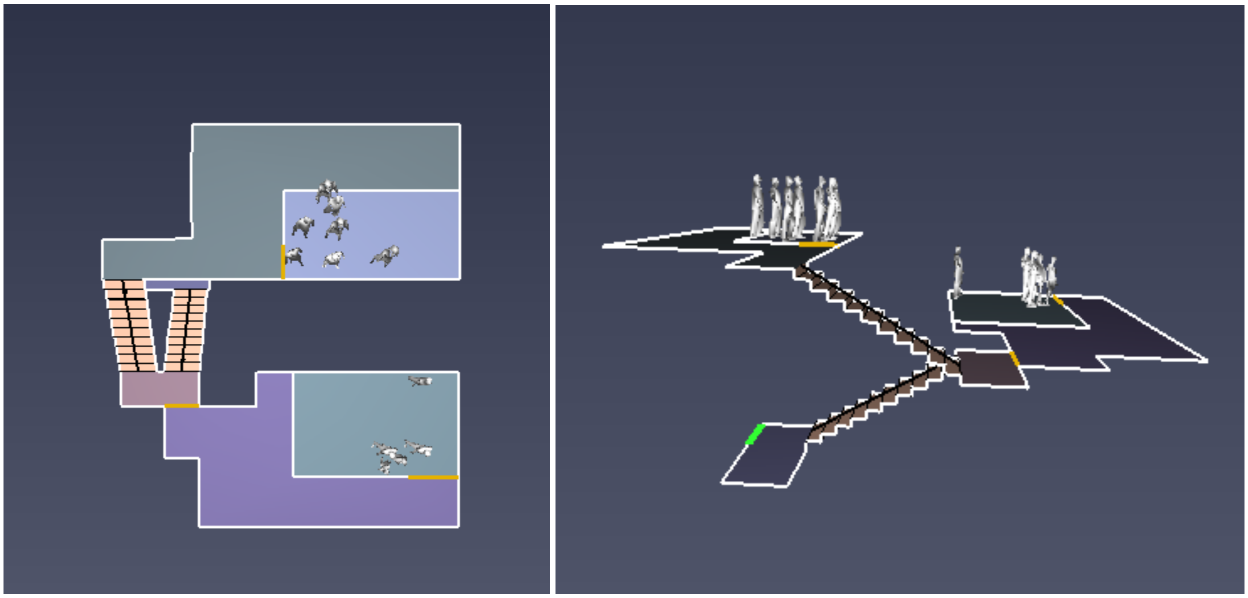


Figure 25: Pathfinder Simulation Geometry (shown with sample occupants).

Before any simulations were run, two hypotheses were made. First, the results of the SFPE mode should agree with the hydraulic model presented in [2]. This should result in the outflow being equal to the sum of the inflows, meaning the flow ratio will be 100%. Second, the results of the steering mode should be similar to the actual empirical data. While it is not expected that the average percent of the expected outflow will be exactly 75%, as observed empirically, it is expected that the flow ratio will be less than that of the SFPE mode.

5.1 PATHFINDER MODELING DATA

A summary of the different occupant combinations for each event is given in Table 6. Full results from the Pathfinder simulations are given in

Appendix 3: Pathfinder Merging Behavior.

Simulation	Floor Occupants	Stair Occupants
1	6	5
2	2	3
3	5	3
4	4	6
5	5	4
6	3	2
7	5	5
8	6	3
9	7	7
10	3	6
11	3	5
12	6	2
13	5	6
14	7	6
15	3	6
16	6	4
17	2	2
18	5	2
19	2	7
20	3	3

Table 6: Occupant Distribution for Pathfinder Simulations.

Mode	Flow Ratio	Standard Deviation
SFPE	66.35	13.96
Steering	81.05	14.21
Overall	73.70	15.77

Table 7: Flow Rate Data for Pathfinder Simulations

The results of the Pathfinder simulation are shown in Table 7 and Figure 26. Unexpectedly, the steering mode yielded a higher flow ratio than the SFPE mode for majority of the merging events. Contrary to expectations, the Steering mode resulted in a 15% higher flow ratio on average, as shown in Table 7.

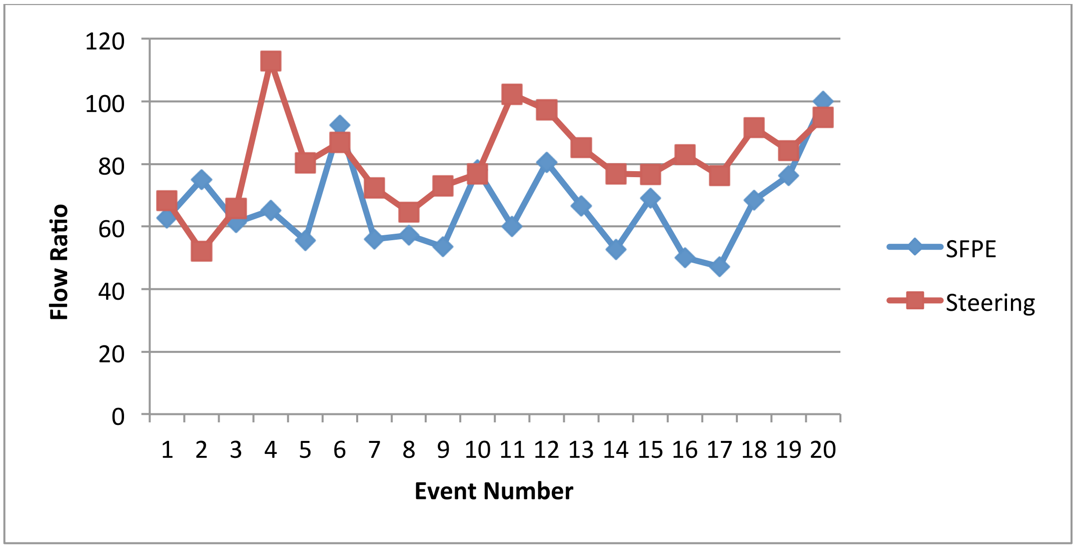


Figure 26: Flow Ratios for SFPE and Steering modes

Next, a similar analysis as done in chapter 4 was conducted for the Pathfinder merging data. The flow ratio was analyzed as a function of the inflow rate and both the stair flow and the floor flow, as shown in Figure 28, Figure 29 and Figure 29. The flow ratio followed a linearly decreasing trend with the inflow rate, with a very high R^2 value for both simulation modes. For the stair and floor flows, there were varying degrees of agreement between the data sets. Similar to the empirical data, the effects of any of the individual source flows were much less apparent then the combined inflow rate. However, both the stair and floor flows still decreased with the flow ratio for both simulation modes.

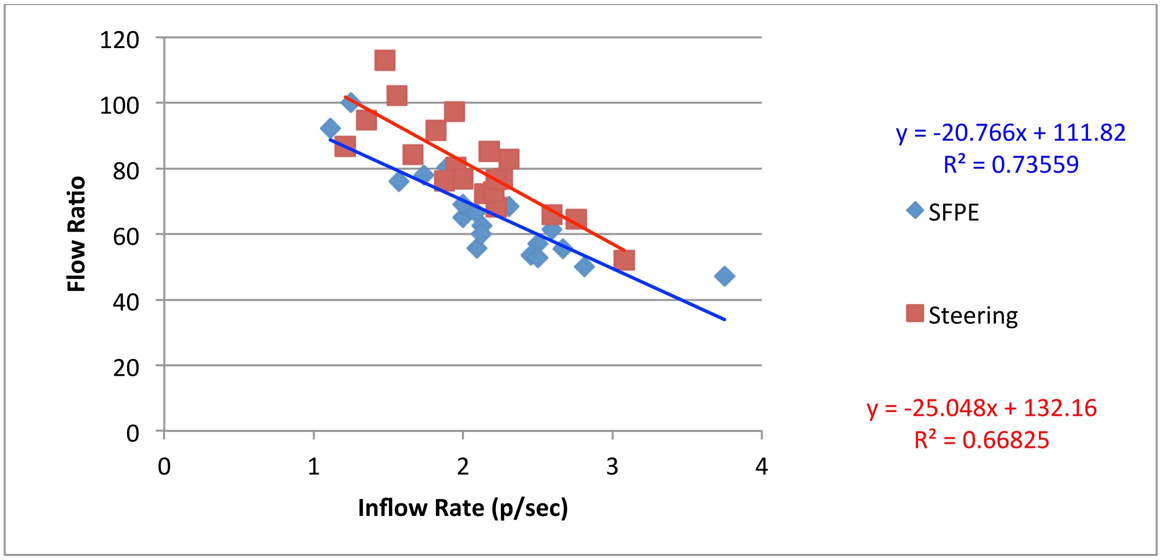


Figure 27: Flow Ratio vs. Inflow Rate (Pathfinder).

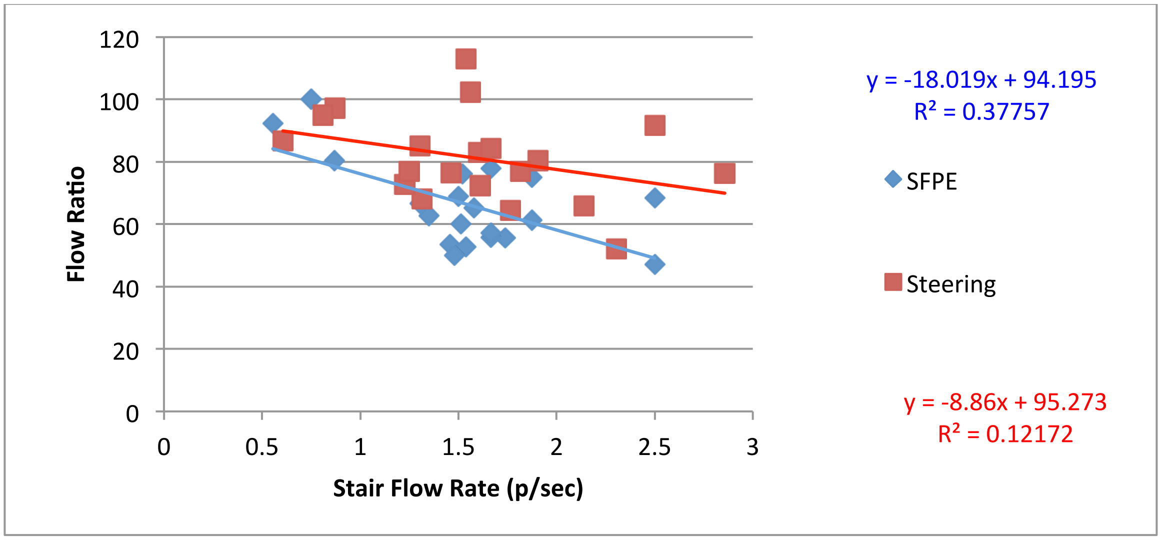


Figure 28: Flow Ratio vs. Stair Flow Rate (Pathfinder).

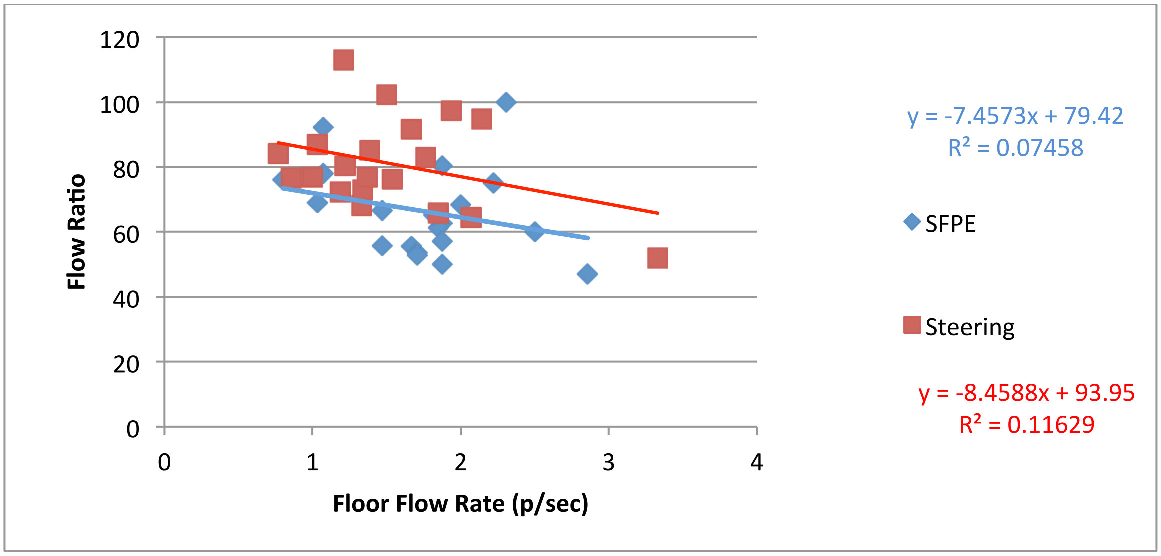


Figure 29: Flow Ratio vs. Floor Flow Rate (Pathfinder).

Finally, the flow ratio was examined as a function of the outflow rate, as shown in Figure 30. The SFPE mode yielded a decreasing linear trend, but the steering mode showed little trend at all.

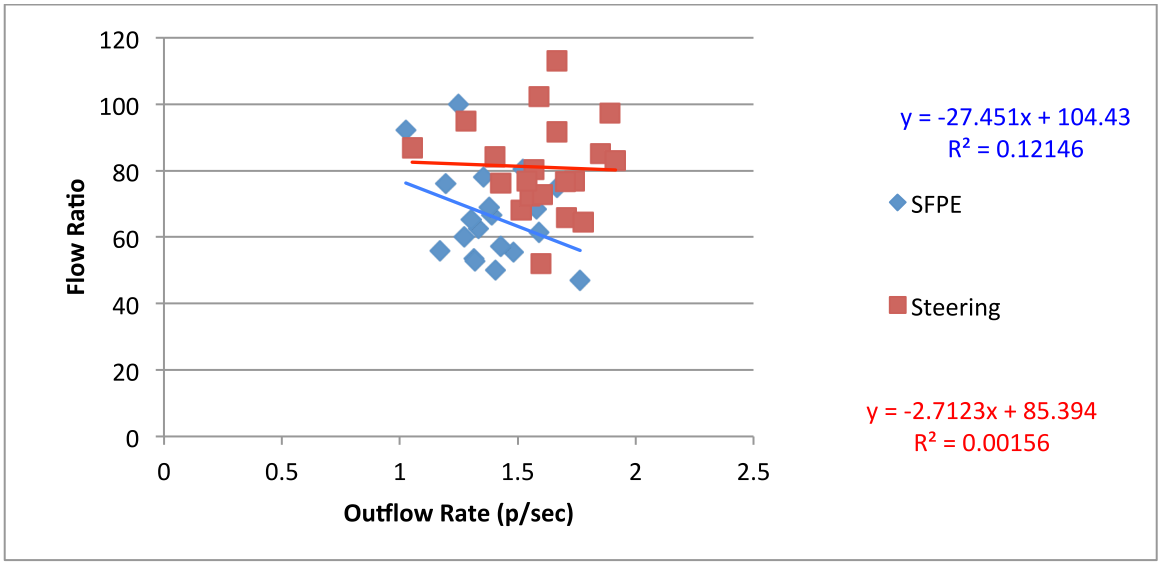


Figure 30: Flow Ratio vs. Outflow Rate (Pathfinder).

5.2 PATHFINDER MODELING ANALYSIS

The data presented in Table 7 and Figure 26 disagrees with the hypotheses made before the Pathfinder analysis began. It was expected that because the SFPE mode operated under the specifications of the hydraulic model presented in [2], the flow ratio would be 100%, meaning that the actual outflow was equal to the inflow. However, the SFPE mode data gave the average flow ratio to be 66%, about 34% less than expected.

Next, the data presented in Figure 27, Figure 28 and Figure 29 agrees with the empirical data presented in Chapter 4. The flow ratio decreases with the inflow rate, and this is shown best when compared to the total inflow, but also to a lesser extent when compared to the individual inflow rates. The data presented in Figure 30 does not agree with the empirical data, as it shows the outflow rate decreasing with the flow ratio. A comparison of the slopes of the fitted trend lines for the flow ratio vs. the in, stair, floor and outflows is given in Table 8.

		Pathfinder	
Flow	Experimental	Steering	SFPE
Inflow	-36.7	-25.0	-20.8
Stair Flow	-14.8	-8.9	-18.0
Floor Flow	2.8	-8.5	-7.5
Outflow	71.1	-2.7	-27.5

Table 8: Slopes of fitted trend lines for flow ratio vs. various flows.

Initially, it was unclear as to why the Pathfinder SFPE mode did not produce the expected merging behavior. Upon further investigation, it was determined that the nature of the hydraulic model offered an explanation. The hydraulic model works on the principle that some path of the egress route, generally a door or stairwell, will act as a controlling element (this is the first order approximation of the model). This element has the lowest maximum flow rate of all elements in the path of egress, thus the time it takes all occupants to travel through this element, plus the time of travel to this element and the time of travel from this element to the exit is the evacuation time. Often, this controlling element is the stairwell door. The hydraulic model gives a maximum flow rate through doors as a function of the door width, and this maximum flow rate is then used in the Pathfinder SFPE mode. Because the stair door often acts as the controlling element, any activity going on beyond the doorway is of no concern when using the hydraulic model. The path beyond the doorway could be wide open or completely blocked, but either way, the model will send occupants through the doorway up to the maximum flow rate of that door. This first scenario seemed to be the problem in the pathfinder model, when it was observed that occupants would pause at a doorway when there was no blockage or obstacle preventing them from passing through it. It appeared that because the occupants could only pass through the door at a certain flow rate, there was an unnecessary delay before each occupant passed through the door. Physically, a group of occupants that was close together entering the door would be much more spaced out after passing through the door. This often created an unnecessary queue that would occur in the simulation, but in reality should not have happened.

Such an observation indicates that regardless of how the SFPE mode actually handles the merging event, the unnecessary queue formed at the stair door prevents Pathfinder from meeting the SFPE merging criteria. From the macroscopic perspective, the SFPE mode still accurately represents the controlling element phenomena, and thus the overall evacuation time is in agreement with the hydraulic model. (Because the controlling element is the stair door, the occupants proceed through the stair door at the maximum flow rate, and thus the merging behavior downstream is irrelevant to the door behavior, and thus the overall evacuation time). The SFPE mode results cannot be compared with the hydraulic model flow calculations in this case.

Overall, the SFPE mode does not agree with the empirical data, nor does it accurately model the merging behavior of the hydraulic model. However, the overall egress times given by Pathfinder's SFPE mode are consistent with those given from the hydraulic model calculations. Macroscopically, this is rather unimportant. Microscopically, however, this finding is significant. Because the SFPE mode yields a flow ratio much less than the 100% expected per the hydraulic model, the number of people on a stair landing during any particular merging event will increase. This could lead to occupants being unable to enter the stairwell during the evacuation simulation when they really should be according the hydraulic model. This microscopic disagreement between the hydraulic model and Pathfinder's SFPE mode could lead to a model user using the SFPE mode thinking that they have modeled the hydraulic calculations when in reality, they have only a similar calculation with the significant difference described above.

Qualitatively, the Pathfinder steering mode results agree with the empirical data. Both show that there is a loss in efficiency during merging events and that the flow ratio is some number below 100%. Quantitatively, the average flow ratio from the empirical data is very close to that of the Pathfinder data. The empirical data yielded an average flow ratio of 75.6% while the Pathfinder data yielded 81.1%. The standard deviation for the empirical data was 23%, placing the Pathfinder data well within one standard deviation of the mean. The small diagreement between these averages is not statistically significant given the high standard deviation. The one area of disagreement between the emprical data and steering mode is seen when comparing the flow ratio to the outflow rate. The empirical data revealed that the flow ratio increases while the outflow rate increases, but the steering mode simulated the flow ratio decreasing as the outflow rate increased.

From the perspective of Pathfinder users and devlopers, the similarity between the simulated and empirically observed merging inefficiencies shows that the program's merging algorithms accurately model occupant merging behavior. Macroscopically, this has some implications. First, if individual merging events are accurately modeled, then the overall building evacuation model should be more accurate. This is a clear benefit to anyone using the software. Second, Pathfinder's accurate representation of the observed merging inefficiency allows model users to examine potential building designs and estimate which design is the most effective in terms of efficient egress. If an engineer is debating on whether three or four stairs are necessary for a building in a performance-based design, Pathfinder's accurate modeling of merging behavior allows the engineer to make a confident decision.

The two points of disagreement between the steering mode and the empirical data are seen in: 1. The flow ratio vs. outflow rate comparison and 2. The quantitative values of the flow ratio. Both of these disagreements should be be reconciled through an improvement of the steering mode behavioral algorithms. Because the algorithms uses a cost-based approach in deciding occupant movement, the cost to merge with another flow of occupants could be increased, which should lower the average flow ratio to be closer to the empirical data. Additionaly, the algorithm should be examined to determine why the merging efficiency is not affected by the outflow rate, and necessary changes should be made to agree with the empirical data.

6. CONCLUSIONS AND FUTURE RESEARCH

In this study, evacuation data from seven different stairwells was examined to better understand non-queued occupant merging in stairwells during egress. Previous studies had only emphasized the composition of the outflow after merging events and deference behavior, but this paper continued on the preliminary work of [1] by comparing the inflow to the outflow. A flow rate analysis was conducted and it was found that the flow ratio, which is the outflow rate from a merging event divided by the inflow rate, was on average 75%. This finding is in direct disagreement with the hydraulic model, which states that these two flow rates should be equal. It was also found that the flow ratio is proportional to the inflow rate and inversely proportional to the outflow rate. Occupant hesitation was noted throughout the merging events, specifically hesitation towards another flow of occupants. Next, a transit time analysis was conducted as one way to quantify the hesitation and it was found that the transit time for both stair and floor occupants increased during merging events. The ratio of the normal transit time to the merging transit time was on average 0.67 for floor occupants and 0.70 for stair occupants. Both the stair and the floor ratios were directly proportional to the flow ratio. Another flow rate analysis was conducted on the Pathfinder simulation data. The Pathfinder steering mode data qualitatively agreed with the empirical data, though quantitatively the data was slightly different. The SFPE mode also agreed with the empirical data, thus it was inconsistent with the hydraulic model. This was unexpected given that the SFPE mode is designed to simulate the hydraulic model.

By far the most important conclusion that can be made from this research is that merging, particularly non-queued merging, has an inherent inefficiency that has received very little attention in previous studies. This inefficiency is shown in the average flow ratios being less than

100%. The hydraulic model, described in [2], states that combined inflow rates into any merging event should equal the outflow rate. The data presented in this paper shows that such a statement is incorrect, and that outflow rate is equal to some percentage of the combined inflows. The observed inefficiency in the empirical data was also seen in the Pathfinder modeling data. Many parameters affecting the flow ratio were observed, including: inflow, stair flow, floor flow, outflow and stair width, but none of these yielded a definitive explanation as to what causes the merging inefficiency itself. An important qualitative observation was made that most occupants hesitate when encountering another flow of people. This hesitation was readily observed visually, and confirmed by the increase in landing transit times during merging.

An important implication of the merging inefficiency is the affect that it has on occupant entering the stairwell landing as a part of the floor flow. As mentioned previously, a low flow ratio over time will lead to a queue, which would prevent occupants from entering the stairwell on their floor of origin. Generally, the main concern in egress is the overall evacuation time, but for occupants on the fire floor, or in phased evacuation scenarios, this becomes very important. If the time to enter the stairwell itself increases as a result of the merging inefficiency, and this was not accounted for the in the life safety RSET calculation then occupants on the fire floor are put in danger. Because the presented data includes only knowledge of what goes on in the stairwell, this phenomena could not be further analyzed.

The agreement between the Pathfinder steering mode and empirical data shows that Pathfinder's behavioral algorithms do a good job of modeling human behavior. This agreement gives credibility to the model when being used to simulate stairwell landing events as part of a building evacuation. While good, the steering mode is not perfect, and the empirical data could be used to improve the model's behavioral algorithms. As seen from the higher average flow ratio, the model should be more conservative in how it handles occupant merging. This could be done by changing the cost value associated with an occupant's decision to move towards another occupant on the stairwell landing. A slightly higher cost to do this would stop occupants from merging with another flow so easily, and would decrease the efficiency of the merging event. Additionally, the model could be improved by changing the behavioral algorithm in such a way as to make the flow ratio increase as the outflow rate increases.

Other conclusions, as stated previously, include different parameters that affect occupant flow ratios and transit times during merging. Low inflows and high outflows indicate that the flow ratio of the merging event will be high, and vice versa. The flow ratio increases slightly with stair width, but does not change with floor number in the building. The flow ratio and transit time ratios are directly proportional and interdependent on one another.

Future research on non-queued occupant merging in stairwells should explore the observed hesitation during merging events. Quantitatively, it is very difficult to analyze this phenomenon, but a number of options could be explored to do so. Potentially, the velocity of occupants could be tracked continuously, which would allow hesitation to be quantified as a reduction in velocity when encountering another flow of people. Another possibility would be to measure the group velocity as a whole and observe the change during merging. Finally, the impact of the observed merging inefficiency on the floor flow rate needs further examination. It is known that the merging inefficiency can lead to a queue forming which would reduce or stop the floor flow, but the implications of this for occupants on the fire floor remains unknown. The goal of this future research should be to definitively state the cause of the merging inefficiency, and explore its application to computer egress models.

Appendix 1: Merging Data

	Event	Floor	Time Interval	Floor Occupants	Stair Occupants	Total Occupants	Floor	Stair	Inflow	Out	Flow Ratio
4A	1	20	1622-1631	4	3	7	0.434	0.377	0.868	0.592	68.20
	2	16	1488-1498	4	4	8	0.373	0.696	0.871	0.829	95.18
	3	16	1498-1508	5	3	8	0.341	0.456	0.798	0.558	69.92
	4	12	1332-1342	5	4	9	0.503	0.504	0.881	0.662	75.14
	5	12	1342-1352	5	5	10	0.591	0.535	1.14	0.71	62.28
	6	12	1352-1365	3	2	5	0.226	0.474	0.445	0.441	99.10
	7	10	1274-1284	3	5	8	0.658	0.574	0.999	0.548	54.85
	8	10	1284-1294	2	4	6	0.556	0.435	0.725	0.551	76.00
	9	10	1294-1303	3	4	7	0.251	0.574	0.753	0.483	64.14
	10	8	1219-1225	4	3	7	0.595	0.526	0.992	0.597	60.18
	11	8	1234-1244	4	4	8	0.468	0.373	0.788	0.412	52.28
	12	8	1244-1254	3	3	6	0.279	0.306	0.617	0.417	67.59
	13	8	1254-1264	4	4	8	0.314	0.468	0.877	0.308	35.12
	14	6	1200-1210	3	2	5	0.497	0.337	0.877	0.647	73.77
4B	1	10	1279-1289	4	5	9	0.442	0.433	0.85	0.685	80.59
	2	10	1289-1299	3	5	8	0.454	0.535	0.936	0.66	70.51
	3	10	1299-1309	3	4	7	0.321	0.35	0.668	0.474	70.96
	4	6	1201-1210	4	3	7	0.343	0.295	0.686	0.661	96.36
	5	6	1220-1230	4	2	6	0.396	0.8	0.627	0.692	110.37
	6	4	1260-1270	2	6	8	0.599	0.588	0.823	0.611	74.24
5A	1	9	809-819	5	5	10	0.468	0.53	1.02	0.531	52.06
	2	7	736-746	5	5	10	0.463	0.587	1.04	0.686	65.96
	3	7	746-756	5	7	12	0.533	0.694	1.27	0.844	66.46
	4	7	756-766	2	8	10	0.524	0.825	1.06	0.47	44.34
	5	5	680-690	8	5	13	0.783	0.495	1.34	1.2	89.55
	6	5	690-700	6	6	12	0.543	0.63	1.12	1.11	99.11
	7	5	700-710	6	6	12	0.72	0.787	1.46	0.904	61.92
	8	5	710-720	4	3	7	0.374	0.782	1.14	0.371	32.54
	9	3	640-650	5	6	11	0.645	0.553	1.11	1.11	100.00
	10	3	650-660	2	9	11	0.855	1.07	1.27	1.01	79.53
	11	3	660-670	2	10	12	0.286	1.09	1.33	0.999	75.11
	12	3	670-680	3	11	14	0.353	1.09	1.53	0.575	37.58
5B	1	9	800-811	5	4	9	0.508	0.462	0.825	0.851	103.15
	2	7	718-728	5	5	10	0.573	0.582	0.943	0.89	94.38
	3	7	728-738	6	7	13	0.568	0.699	1.32	0.7	53.03
	4	5	600-610	5	7	12	0.545	0.705	1.26	0.843	66.90
	5	5	610-620	5	5	10	0.506	0.452	0.959	0.661	68.93
	6	5	620-630	4	7	11	0.378	0.711	1.18	0.531	45.00
	7	5	630-640	4	6	10	0.41	0.543	0.978	0.678	69.33
	8	5	640-655	5	8	13	0.419	0.63	1.08	0.529	48.98
	9	3	505-510	4	3	7	0.898	0.531	1.42	0.972	68.45

7_3	1	15	1036-1046	5	5	10	0.593	0.526	1.13	0.731	64.69
	2	15	1064-1074	4	3	7	0.612	0.258	0.759	0.578	76.15
	3	15	1091-1101	4	3	7	0.357	0.625	0.843	0.446	52.91
	4	13	966-976	2	2	4	0.769	0.849	0.987	0.761	77.10
	5	13	1008-1013	3	3	6	0.521	0.673	1.3	0.63	48.46
	6	11	927-937	6	2	8	0.592	0.348	0.829	0.624	75.27
	7	11	937-947	2	4	6	0.526	0.441	0.734	1.11	151.23
	8	11	997-1007	3	4	7	0.38	0.449	0.786	0.406	51.65
	9	9	837-847	4	2	6	0.475	0.565	0.784	0.537	68.49
	10	9	892-902	3	4	7	0.778	0.391	0.778	0.546	70.18
	11	7	755-765	4	3	7	0.468	0.227	0.676	0.367	54.29
	12	7	765-775	4	4	8	1.07	0.475	1.04	0.527	50.67
	13	7	822-832	4	5	9	0.611	0.491	0.982	0.4	40.73
	14	7	832-842	3	2	5	0.338	0.184	0.458	0.23	50.22
	15	7	859-869	2	5	7	0.361	0.505	0.742	0.76	102.43
8N	1	26	1583-1593	3	4	7	0.289	0.478	0.829	0.737	88.90
	2	20	1455-1465	4	4	8	0.432	0.651	0.835	0.623	74.61
	3	20	1465-1475	4	7	11	0.566	0.806	1.2	1.01	84.17
	4	20	1475-1485	3	4	7	0.357	0.385	0.669	0.89	133.03
	5	20	1485-1495	5	6	11	0.48	0.669	1.17	0.747	63.85
	6	20	1495-1505	4	4	8	0.317	0.499	0.912	0.642	70.39
	7	20	1505-1515	3	6	9	0.317	0.731	0.884	0.596	67.42
	8	20	1554-1564	5	6	11	0.45	0.672	1.13	0.743	65.75
	9	18	1435-1446	4	6	10	0.414	0.579	0.86	0.805	93.60
	10	18	1521-1527	2	3	5	0.515	0.833	1.23	0.612	49.76
	11	14	1664-1674	2	7	9	0.602	1.26	1.37	0.922	67.30
	12	11	1586-1596	2	5	7	0.556	0.56	0.74	0.683	92.30
	13	11	1620-1630	2	7	9	0.111	0.743	0.862	0.74	85.85
	14	9	1492-1502	3	4	7	0.244	0.365	0.727	0.546	75.10
	15	9	1546-1556	3	8	11	0.425	0.829	1.03	1.01	98.06
	16	9	1556-1566	5	4	9	0.54	0.445	1.03	0.641	62.23
	17	9	1583-1593	3	6	9	0.349	0.633	0.86	0.546	63.49
	18	9	1710-1720	3	6	9	0.382	0.572	0.915	0.561	61.31
	19	5	1465-1475	4	6	10	0.342	0.7	1.02	0.927	90.88
	20	5	1549-1559	5	7	12	0.454	0.882	1.24	0.894	72.10
	21	5	1567-1577	3	7	10	0.855	0.863	1.23	0.879	71.46
	22	4	1407-1417	2	6	8	0.412	0.517	0.723	0.598	82.71
	23	4	1417-1427	2	3	5	0.476	0.343	0.572	0.768	134.27
	24	4	1427-1437	2	7	9	0.34	0.756	0.945	0.901	95.34
8S	1	28	1650-1660	5	2	7	0.612	0.526	0.917	0.544	59.32
	2	26	1577-1590	4	10	14	0.529	0.737	1.06	1.04	98.11
	3	26	1646-1652	2	5	7	0.41	0.778	1.29	0.723	56.05
	4	22	1474-1484	4	4	8	0.541	0.45	0.941	0.971	103.19
	5	22	1490-1500	6	2	8	0.644	0.189	0.902	0.78	86.47

	6	22	1500-1509	4	3	7	0.389	0.885	0.718	0.527	73.40
	7	18	1321-1331	3	4	7	0.425	0.493	0.813	0.81	99.63
	8	18	1331-1341	3	5	8	0.238	0.582	0.832	0.699	84.01
	9	18	1341-1351	4	5	9	0.5	0.579	0.85	0.888	104.47
	10	18	1380-1391	3	5	8	0.487	0.526	0.766	0.777	101.44
	11	18	1395-1405	3	7	10	1.02	0.74	1.03	0.739	71.75
	12	16	1705-1715	2	5	7	0.833	0.557	0.832	0.661	79.45
	13	14	1638-1646	2	2	4	0.971	0.493	0.85	1.02	120.00
	14	11	1540-1551	2	5	7	0.621	0.686	1.03	0.772	74.95
	15	9	1480-1488	3	5	8	0.411	0.709	1.03	0.936	90.87
	16	9	1505-1516	5	7	12	0.449	0.673	1	0.8	80.00
	17	5	1374-1387	6	8	14	0.412	0.697	1.07	0.8	74.77
	18	5	1474-1480	3	3	6	0.4	0.399	0.973	0.452	46.45
	19	4	1290-1305	4	6	10	0.343	0.96	1.02	0.862	84.51
	20	4	1324-1334	2	8	10	0.18	1.05	1.18	0.681	57.71
	21	4	1334-1340	2	4	6	0.217	0.667	1.06	0.728	68.68

Note: All time intervals are in seconds and are taken from the corresponding floor video. All flow rates are in people/second.

APPENDIX 2: TRANSIT TIME DATA

TRANSIT TIME RAW DATA

Stair	Floor	Merge Periods	Stair Average	Floor Average	Merge Stair Average	Merge Floor Average	Stair Ratio	Floor Ratio	Stair Change	Floor Change
5A	9	809-819	15.43	3.70	15.24	5.94		0.62	-0.19	2.24
	7	736-746	6.98	4.11	7.56	4.80	0.92	0.86	0.58	0.69
	7	746-756	6.98	4.11	8.98	5.23	0.78	0.79	2.00	1.12
	5	680-690	3.11	3.44	5.12	3.85	0.61	0.89	2.01	0.41
	5	690-700	3.11	3.44	6.56	5.21	0.47	0.66	3.46	1.77
	5	700-710	3.11	3.44	9.28	5.18	0.33	0.66	6.18	1.74
	5	710-720	3.11	3.44	15.43	7.94	0.20	0.43	12.33	4.50
	3	640-650	6.45	4.43	9.49	5.73	0.68	0.77	3.04	1.30
	3	650-660	6.45	4.43	7.07	4.62	0.91	0.96	0.62	0.19
	3	660-670	6.45	4.43	7.40	9.33	0.87	0.47	0.95	4.90
	3	670-680	6.45	4.43	12.97	15.88	0.50	0.28	6.52	11.45
5B	9	800-811	5.40	3.72	7.29	5.70	0.74	0.65	1.89	1.98
	7	718-728	6.06	5.16	8.92	6.55	0.68	0.79	2.86	1.39
	7	728-738	6.06	5.16	10.97	6.63	0.55	0.78	4.91	1.47
	5	600-610	5.84	2.59	6.43	5.96	0.91	0.43	0.59	3.37
	5	610-620	5.84	2.59	10.33	7.24	0.57	0.36	4.49	4.65
	5	620-630	5.84	2.59	12.23	7.44	0.48	0.35	6.39	4.86
	5	630-640	5.84	2.59	12.63	7.60	0.46	0.34	6.79	5.01
	5	640-655	5.84	2.59	17.71	11.11	0.33	0.23	11.87	8.52
	3	505-510	3.91	3.64	5.74	3.91	0.68	0.93	1.83	0.27
4A	20	1622-1631	4.20	4.72	6.91	4.82	0.61	0.98	2.70	0.10
	16	1488-1498	5.45	5.21	11.13	5.27	0.49	0.99	5.68	0.06
	16	1498-1508	5.45	5.21	9.79	6.36	0.56	0.82	4.34	1.15
	12	1332-1342	0.00	5.41	10.45	4.56				-0.86
	12	1342-1352	0.00	5.41	10.54	6.30				0.89
	12	1352-1365	0.00	5.41	9.21	9.39				3.97
	10	1274-1284	5.68	0.00	8.72	5.37			3.05	
	10	1284-1294	5.68	0.00	11.51	7.89			5.84	
	10	1294-1303	5.68	0.00	11.03	7.13			5.35	
	8	1219-1225	4.81	3.67	9.42	3.80	0.51	0.97	4.61	0.13
	8	1234-1244	4.13	3.67	11.90	6.93	0.35	0.53	7.77	3.26
	8	1244-1254	4.13	3.67	11.71	8.16	0.35	0.45	7.59	4.49
	8	1254-1264	4.13	3.67	19.49	6.95	0.21	0.53	15.36	3.28
	6	1200-1210	4.72	0.00	6.48	4.41			1.76	

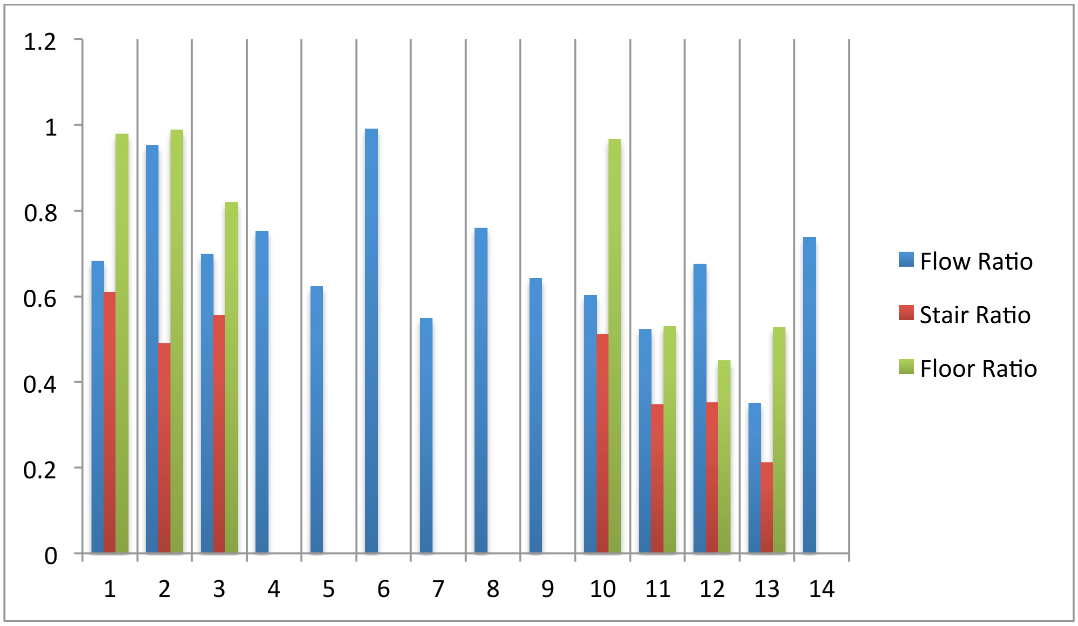
4B	10	1279-1289	4.32	0.00	5.93	4.88			1.61	
	10	1289-1299	3.96	0.00	9.40	5.65			5.44	
	10	1299-1309	3.96	0.00	12.90	6.98			8.94	
	6	1201-1210	0.00	4.95	7.23	5.01				0.05
	6	1220-1230	0.00	4.95	7.20	4.94				-0.01
	4	1260-1270	9.35	5.62	8.49	6.65	1.10	0.84	-0.86	1.04
7_3	15	1036-1046	5.34	4.04	9.03	9.54	0.59	0.42	3.69	5.50
	15	1064-1074	5.34	4.04	10.59	4.89	0.50	0.83	5.25	0.85
	15	1091-1101	5.34	4.04	8.36	10.63	0.64	0.38	3.02	6.59
	13	966-976	4.61	4.32	3.57	4.65	1.29	0.93	-1.04	0.33
	13	1008-1013	4.61	4.32	9.45	9.42	0.49	0.46	4.84	5.10
	11	927-937	5.57	4.77	7.27	6.62	0.77	0.72	1.70	1.85
	11	937-947	5.57	4.77	5.62	7.58	0.99	0.63	0.05	2.81
	11	997-1007	5.57	4.77	10.23	14.65	0.54	0.33	4.66	9.88
	9	837-847	9.94	6.16	9.91	5.77	1.00	1.07	-0.03	-0.39
	9	892-902	9.94	6.16	10.54	6.48	0.94	0.95	0.59	0.33
	7	755-765	5.88	4.60	8.00	5.28	0.74	0.87	2.12	0.68
	7	765-775	5.88	4.60	12.21	7.88	0.48	0.58	6.33	3.27
	7	822-832	5.88	4.60	10.80	7.56	0.54	0.61	4.92	2.96
	7	832-842	5.88	4.60	17.29	8.22	0.34	0.56	11.41	3.62
	7	859-869	5.88	4.60	11.05	10.41	0.53	0.44	5.16	5.81
8_N	26	1583-1593	0.00	4.29	5.31	5.32				1.03
	20	1455-1465	5.49	3.68	7.08	4.99	0.77	0.74	1.59	1.31
	20	1465-1475	5.49	3.68	9.06	6.13	0.61	0.60	3.57	2.45
	20	1475-1485	5.49	3.68	8.48	6.34	0.65	0.58	2.99	2.65
	20	1485-1495	5.49	3.68	9.56	6.11	0.57	0.60	4.07	2.43
	20	1495-1505	5.49	3.68	11.22	8.09	0.49	0.46	5.73	4.41
	20	1505-1515	5.49	3.68	9.98	6.76	0.55	0.54	4.50	3.08
	20	1554-1564	5.49	3.68	8.54	6.47	0.64	0.57	3.05	2.79
	18	1435-1446	4.26	6.59	5.26	4.76	0.81	1.38	1.00	-1.83
	18	1521-1527	4.26	6.59	9.22	8.83	0.46	0.75	4.96	2.24
	14	1664-1674	5.02	4.49	6.93	5.71	0.72	0.79	1.91	1.22
	11	1586-1596	5.77	3.30	5.61	5.23	1.03	0.63	-0.16	1.93
	11	1620-1630	5.77	3.30	6.23	5.94	0.93	0.56	0.46	2.64
	9	1492-1502	2.96	3.78	3.39	4.93	0.87	0.77	0.44	1.15
	9	1546-1556	2.96	3.78	6.10	5.52	0.48	0.69	3.14	1.73
	9	1556-1566	2.96	3.78	8.02	6.60	0.37	0.57	5.06	2.82
	9	1583-1593	2.96	3.78	12.90	7.21	0.23	0.52	9.94	3.42
	9	1710-1720	2.96	3.78	13.74	7.21	0.22	0.52	10.78	3.43
	5	1465-1475	2.61	3.57	3.54	4.18	0.74	0.85	0.93	0.62
	5	1549-1559	2.61	3.57	6.73	5.18	0.39	0.69	4.12	1.62

	5	1567-1577	2.61	3.57	5.06	4.20	0.52	0.85	2.45	0.64
	4	1407-1417	2.84	3.91	3.58	4.04	0.79	0.97	0.74	0.13
	4	1417-1427	2.84	3.91	3.85	4.22	0.74	0.93	1.00	0.31
	4	1427-1437	2.84	3.91	3.88	3.94	0.73	0.99	1.03	0.02
8_S	28	1650-1660	2.77	2.86	4.47	6.63	0.62	0.43	1.70	3.76
	26	1577-1590	1.47	0.00	1.74	4.25			0.27	
	26	1646-1652	1.47	0.00	5.25	6.24			3.78	
	22	1474-1484	0.00	0.00	2.32	3.39				
	22	1490-1500	0.00	0.00	2.74	2.85				
	22	1500-1509	0.00	0.00	5.18	6.59				
	18	1321-1331	3.10	3.35	1.95	5.10	1.59	0.66	-1.15	1.75
	18	1331-1341	3.10	3.35	2.54	3.94	1.22	0.85	-0.56	0.59
	18	1341-1351	3.10	3.35	2.51	3.22	1.23	1.04	-0.58	-0.13
	18	1380-1391	3.10	3.35	4.41	4.55	0.70	0.74	1.32	1.20
	18	1395-1405	3.10	3.35	4.65	3.72	0.67	0.90	1.56	0.38
	16	1705-1715	1.82	2.90	4.32	2.65	0.42	1.09	2.50	-0.25
	14	1638-1646	2.11	2.82	1.54	2.05	1.36	1.38	-0.56	-0.77
	11	1540-1551	2.42	2.86	1.97	3.08	1.22	0.93	-0.44	0.22
	9	1480-1488	2.30	2.22	4.36	2.81	0.53	0.79	2.06	0.59
	9	1505-1516	2.30	2.22	3.95	3.85	0.58	0.58	1.65	1.63
	5	1374-1387	3.21	2.47	5.06	4.26	0.63	0.58	1.85	1.79
	5	1474-1480	3.21	2.47	3.83	4.01	0.84	0.62	0.61	1.53
	4	1290-1305	1.99	2.92	3.24	3.25	0.61	0.90	1.25	0.33
	4	1324-1334	1.99	2.92	4.23	4.15	0.47	0.70	2.24	1.23
	4	1334-1340	1.99	2.92	4.60	5.17	0.43	0.56	2.61	2.26

Note: Shaded cells indicate that the normal transit time could not be calculated for the given landing because no occupants passed through the landing before merging began. Landings where this was present have no calculated ratio, as there is not time to compare to.

FLOW, STAIR AND FLOOR RATIOS

4A



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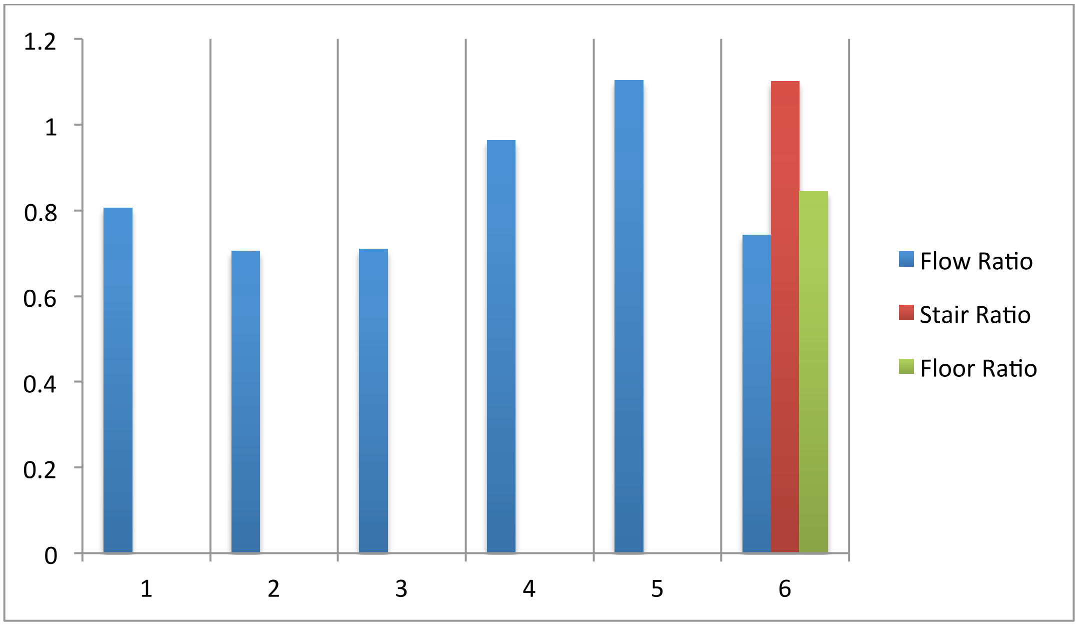

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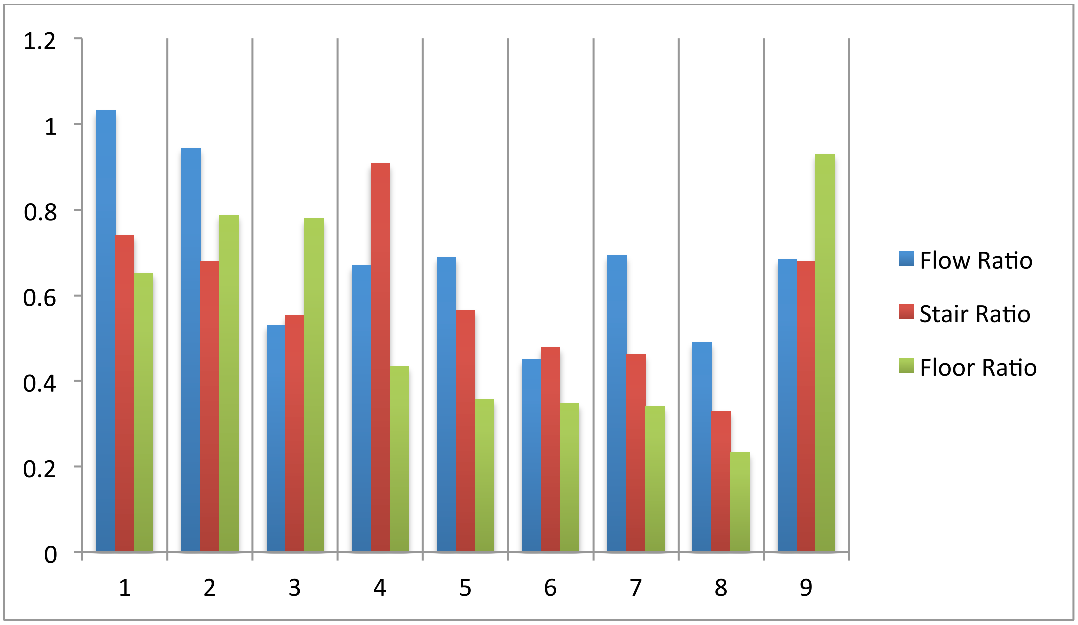
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8
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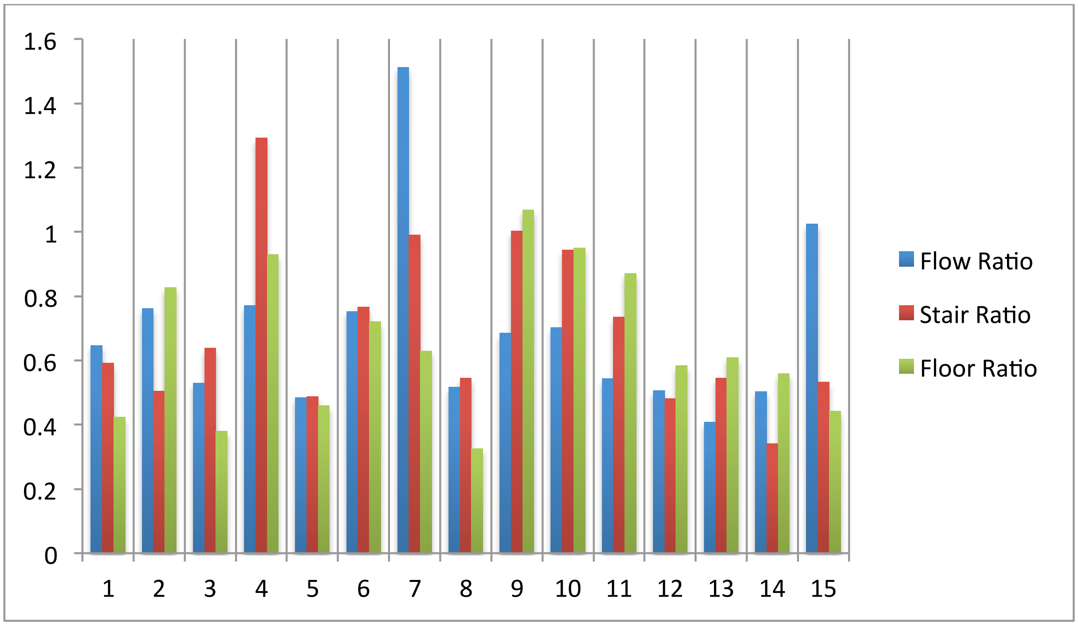
Flow Ratio
Stair Ratio
Floor Ratio

7_3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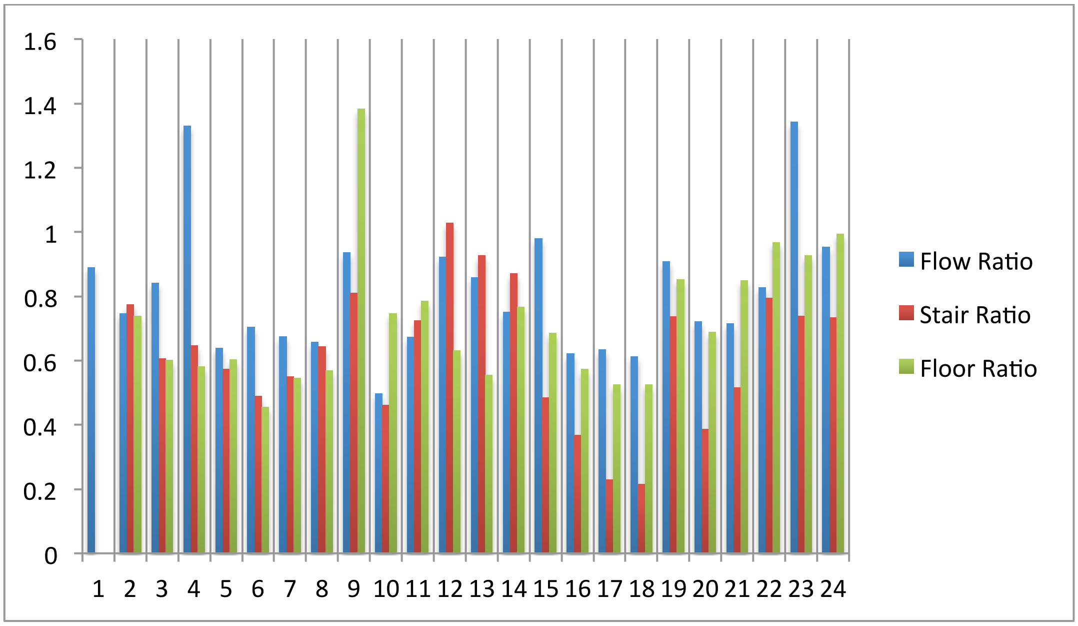
Flow Ratio
Stair Ratio
Floor Ratio

8N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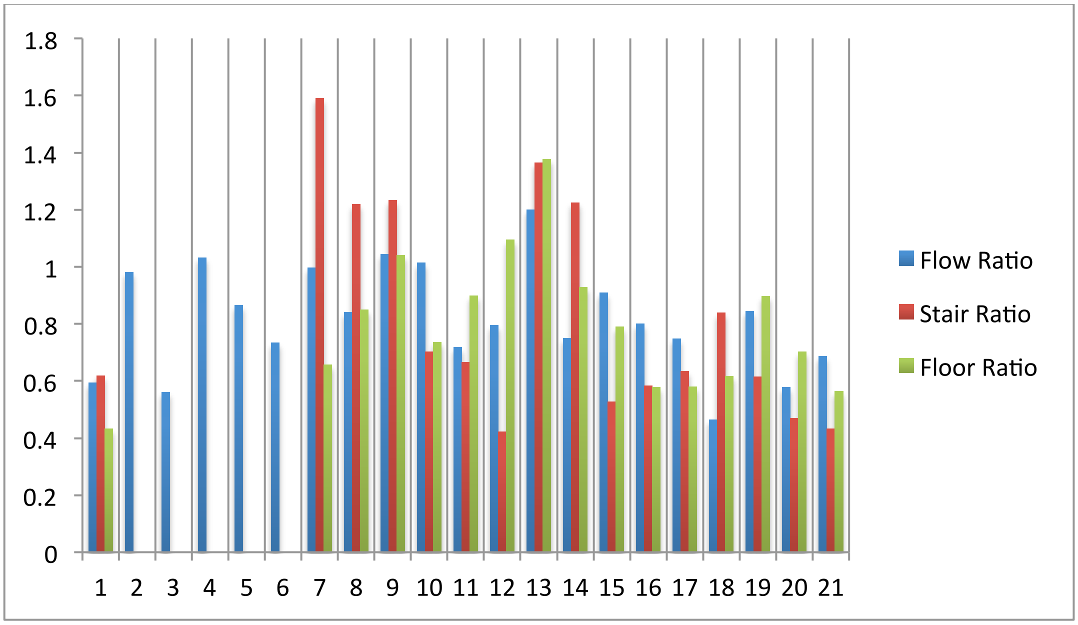
Floor Ratio

8S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Flow Ratio
Stair Ratio
Floor Ratio

APPENDIX 3: PATHFINDER MERGING BEHAVIOR

Event	Floor Flow	Stair Flow	Floor Occupants	Stair Occupants	Out Flow	Inflow Sum	Flow Ratio	Type of Merge
1	1.875	1.35	6	5	0.8	3.225	24.81	SFPE
1	1.333	1.3157	6	5	0.909	2.6487	34.32	Steering
2	2.222	1.875	2	3	0.833	4.097	20.33	SFPE
2	3.33	2.307	2	3	0.8	5.637	14.19	Steering
3	1.85	1.875	5	3	1.136	3.725	30.50	SFPE
3	1.85	2.14	5	3	1.219	3.99	30.55	Steering
4	1.818	1.5789	4	6	0.579	3.3969	17.04	SFPE
4	1.212	1.538	4	6	0.7407	2.75	26.93	Steering
5	1.666	1.739	5	4	0.9259	3.405	27.19	SFPE
5	1.219	1.9047	5	4	0.9803	3.1237	31.38	Steering
6	1.071	0.555	3	2	0.769	1.626	47.29	SFPE
6	1.0344	0.606	3	2	0.7894	1.6404	48.12	Steering
7	1.4705	1.666	5	5	0.6493	3.1365	20.70	SFPE
7	1.19	1.612	5	5	0.862	2.802	30.76	Steering
8	1.875	1.666	6	3	1.071	3.541	30.25	SFPE
8	2.0689	1.764	6	3	1.333	3.8329	34.78	Steering
9	1.707	1.458	7	7	0.70707	3.165	22.34	SFPE
9	1.34	1.228	7	7	0.8641	2.568	33.65	Steering
10	1.071	1.666	3	6	0.508	2.737	18.56	SFPE
10	1	1.818	3	6	0.5769	2.818	20.47	Steering
11	2.5	1.515	3	5	0.5454	4.015	13.58	SFPE
11	1.5	1.5625	3	5	0.6818	3.0625	22.26	Steering
12	1.875	0.8695	6	2	1.304	2.7445	47.51	SFPE
12	1.935	0.86956	6	2	1.621	2.80456	57.80	Steering
13	1.4705	1.304	5	6	0.6944	2.7745	25.03	SFPE
13	1.388	1.304	5	6	0.9259	2.692	34.39	Steering
14	1.707	1.538	7	6	0.7692	3.245	23.70	SFPE
14	1.372	1.25	7	6	1.014	2.622	38.67	Steering
15	1.0344	1.5	3	6	0.5172	2.5344	20.41	SFPE
15	0.857	1.46	3	6	0.638	2.317	27.54	Steering
16	1.875	1.48	6	4	0.9375	3.355	27.94	SFPE
16	1.7647	1.6	6	4	1.2765	3.3647	37.94	Steering
17	2.857	2.5	2	2	1.176	5.357	21.95	SFPE
17	1.538	2.857	2	2	0.95238	4.395	21.67	Steering
18	2	2.5	5	2	1.315	4.5	29.22	SFPE
18	1.666	2.5	5	2	1.3888	4.166	33.34	Steering
19	0.8	1.521	2	7	0.2985	2.321	12.86	SFPE
19	0.769	1.666	2	7	0.3508	2.435	14.41	Steering
20	2.307	0.75	3	3	0.75	3.057	24.53	SFPE
20	2.142	0.8108	3	3	0.76923	2.9528	26.05	Steering

Pathfinder Model Inputs:

Steering Mode:

Time Step: 0.025 seconds

3D Output Frequency: 0.25 seconds

CSV Output Frequency: 1.0 second

Runtime Output Frequency: 0.5 seconds

Max Agent Radius Trim Error: 2.54 cm

Constrain Edge Length: No

Steering Update Interval: 0.1 seconds

Collision Handling: Yes

Inertia: Yes

SFPE Mode:

Time Step: 0.025 seconds

3D Output Frequency: 0.25 seconds

CSV Output Frequency: 1.0 second

Runtime Output Frequency: 0.5 seconds

Max Agent Radius Trim Error: 2.54 cm

Constrain Edge Length: No

Add Basic Collisions: No

Max Room Density: 1.88 persons/m^2

Door Boundary Layer: 15.0 cm

Door Flow Rate: Use Max Flow

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