ABSTRACT

Title of Document: OBSERVED TRENDS IN HUMAN BEHAVIOR PHENOMENA WITHIN HIGH-RISE STAIRWELLS

Andrew Patrick Leahy, Master of Science, 2011

Directed By: Professor and Chair, Dr. James Milke,
Department of Fire Protection Engineering

Sections of four stairwells within two different high-rise office buildings are examined to observe trends in specific human behavior phenomena, and the effects that these actions may have on descent times and flows of the descending populations. Human behavior phenomena analyzed are platoon movement, passing behavior, and merging behavior. Platoons are found to move in three distinct patterns: platoon 1) elongation, 2) compression, 3) equilibrium. Passing and merging behavior demographics based on gender and exit lane usage are presented. In addition, descent time patterns of those following passing events and observed flows of occupants after a merging event are presented.

OBSERVED TRENDS IN HUMAN BEHAVIOR PHENOMENA WITHIN HIGH-RISE STAIRWELLS

By

Andrew Patrick Leahy

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Advisory Committee:
Professor and Chair Dr. James Milke, Chair
Associate Professor Dr. Arnaud Trouve
Dr. Erica Kuligowski

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Chapter 1: Introduction

The following study is the second part of a three year grant funded by the National Institute of Standards and Technology (NIST) focusing on people movement in high-rise stairwells during fire drills. Life safety is an important aspect within the fire protection engineering community that is discussed in detail in the Life Safety Code, NFPA 101 [1]. The main objective of life safety during fire situations is to allow for occupants within a building to reach an area of safety before untenable conditions occur. The time that an occupant takes to exit the building or reach an area of refuge is greatly affected by the means of egress. Chapter 7 of NFPA 101 focuses on the means of egress and defines it as "a continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three separate and distinct parts: (1) the exit access, (2) the exit, and (3) the exit discharge" [1]. The current study focuses on the exit of high-rise buildings, namely the exit stairwells.

Throughout the literature regarding emergency human movement, the available safe egress time (ASET) and the required safe egress time (RSET) are main points of interest for performance-based designs, so it is beneficial to define and discuss these concepts. The ASET is "the whole time from fire ignition to the time untenable conditions occur in the evacuation route" [2]. Note that untenable conditions are not only conditions which cause fatality, but are those conditions which cause the inability of the occupant to self-evacuate. The RSET is "the time required for occupants to reach an area of safety" [2]. Therefore, the ASET must always be greater than the RSET to ensure the safety of the occupants. Although these concepts may seem straightforward, the prediction of these times (especially the RSET) can be very complex. The current study solely involves the RSET.

Discrete time intervals combine to form the entire RSET. These intervals are the time from ignition to detection (t_d), the time from detection to notification (t_n), the time from notification until evacuation commences ($t_{p\text{-}e}$), and the time from the start of evacuation until safety is reached (t_e) [3]. The sum of the detection phase, notification phase, pre-evacuation phase, and evacuation phase make up the total RSET [3]:

$$RSET=t_d+t_n+t_{p\text{-}e}+t_e \tag{1}$$

The detection and notification phases usually depend on a variety of technical factors involving a building's detection and alarm systems. The pre-evacuation and evacuation phases, on the other hand, are the primary phases that involve human decisions and movement. The current study focuses solely on the evacuation phase of the RSET.

The fire protection community uses the hydraulic model in assessing emergency movement. The basic hydraulic model is used to give an estimation of t_e in equation (1). Although the hydraulic model is employed extensively in the field, its estimation of evacuation time is usually optimistic because of the simplicity of the model [3]. Within the model, individuals are all the same (i.e. size, gender, speed) and move like water molecules through a pipe; however, human interaction and experience tells us this is not the case. The hydraulic model does not account for differences in human abilities, let alone differences in human behavior [2, 3, 4]. The main purpose of the current study, along with other human behavior studies, is to improve computer evacuation models by exploring factors not considered in the hydraulic model. These improvements will hopefully lead to better RSET predictions.

The following paper investigates the possible effects that three types of distinct human behavior phenomena have on the overall flow of descending occupants in high-rise stairwells during unannounced fire drills. The three types of human behavior studied are platoon movement, passing behavior, and merging behavior.

A "platoon" is not explicitly defined within the fire protection literature, but the concept has been studied in the civil engineering community in regards to traffic flow theory. In the current study, a platoon is defined as a group of individuals who are spatially close and descend in the same approximate flow pattern. From the data collected by NIST, it is observed that people tend to travel in platoons, as opposed to being uniformly spaced as they move in high-rise stairwells. The current study attempts to show that the formation of platoons happens more often than not, and attempts to determine the effects that these groups have on the overall egress performance of the population. Platoon descent time analyses where no merging occurs are presented to show patterns in platoon movement, and the differing flow patterns seen in the two different buildings analyzed.

Passing and merging behaviors are also explored in the current paper to determine the effects that these specific types of phenomena have on the egress performance of the descending population. The passing and merging behaviors are examined relative to the exit lane used to descend the stairwell and gender characteristics. Sections in the stairwells where no queues are found to occur are analyzed to determine how descent times are affected by passing events, and how flows are affected by merging events.

The hypotheses on human movement during evacuation within high-rise stairwells tested in the current study are the following:

1. People do not move as the hydraulic model predicts and human behavior is the primary cause.

2. Physical movement platoons exist within high-rise stairwell evacuations and display similar patterns to vehicle transportation platoons.
3. There are demographic trends associated with passing and merging events.
4. The descent times of those occupants closely following a passing event are negatively impacted by the event.
5. The sum of the inflows associated with a merger does not equal the merger outflow.

These hypotheses are tested by examining the descent times, demographics (specifically, gender and exit lane usage), and flows of the descending populations within four stairwells during total evacuations of two different high-rise buildings. The main purpose of this study is to provide computer evacuation models with actual evacuation data trends to better predict the required safe egress time of evacuating populations.

Chapter 2: Background Information

The following chapter reviews the current research available on people movement during emergency situations, as well as research pertaining to platoons. In Section 2.1, a detailed discussion of the hydraulic model is presented. In Section 2.2, a discussion of the current computer evacuation modeling used in the fire protection engineering community is presented. Following 2.2, studies within both the fire protection and transportation engineering communities regarding platoons are given and discussed. Then, a literature review on merging behavior during evacuations is given. Also, sources regarding the validity of fire drill experiments are presented to help validate the data used in this study.

2.1 The Hydraulic Model

The model that is often used to predict evacuation times during emergency movement is the hydraulic model. The engineering calculations of the hydraulic model were originally developed by Nelson and MacLenan [5] based on the human movement research contributed by Predtechenskii and Milinskii [6], Fruin [7], and Pauls [8, 9]. Within the model, three important parameters are used to describe the movement of people. These three parameters are density, speed, and flow. The backbone of the model is that speed of movement is a function of the population density (i.e. crowdedness) [3]. Before a quantification of these parameters is presented, the assumptions of the calculations and the concept of effective width [8] are discussed.

The equations of the hydraulic model assume the following:

1. “All persons start to evacuate at the same instant.
2. Occupant flow does not involve interruptions caused by evacuee decisions.
3. The evacuees are free of impairments/ disabilities that impede their movement” [3].

These assumptions provide the engineer with a relatively simple way to quantify the density, speed, and flow of the population in order to predict the evacuation time. Many factors and behaviors that can affect the evacuation time are excluded by these assumptions, so in practice the engineer usually adjusts the predicted time by a safety factor to account for the assumptions made. Some of the factors and behaviors affecting evacuation time are outlined by Gwynne and Rosenbaum [3]:

- Procedural (active fire protection, emergency signage, notification system, emergency training, performance of fire drills, false/inaccurate alarms, staff/fire warden)
- Organizational (safety culture, normal use of structure, security procedures, communication system, existence of social hierarchy, distribution and size of population, nature of population)
- Environmental/Scenario-Based (presence of fire effluent, background pollution, lighting levels, debris, presence of fatalities, structural damage, loss of routes)
- Architectural/Structural (building type, physical dimensions, geometry of enclosure, number and arrangement of egress routes, complexity of space, visual separation, lighting and non-emergency signage, extent of passive fire protection)
- Individual (cognitive abilities, language/culture, exposure to cues, location, fatigue, general health, sensory/cognitive impairment, size, experience, information levels, familiarity, role, responsibility, age, gender, activity, social affiliation, engagement, commitment, physical abilities/limitations, proximity to incident, motivation, status)

Numerous studies have shown that the width of a component (i.e. stairwell, corridor, aisle, ramp, doorway) through which people evacuate has a linear effect on the flow of people through that component. In other words, the flow through a component is linearly dependent on the width of that component; the greater the width, the greater the flow capacity. The clear width (total width from wall to wall) of the component, however, is not the width that is used in the hydraulic equations. The usable width, or the effective width, is the width that the model uses.

Jake Pauls first coined the term “effective width” while conducting high-rise building evacuation experiments in Canada during the 1970s [8]. The effective width is the width that is actually used by occupants. The effective width can be measured by subtracting the boundary layer from the clear width of a component. The boundary layer is the space that an occupant keeps between themselves and an object within the egress component (i.e. walls, handrails, benches, obstacles). Personal space and lateral body sway are factors that contribute to the space that occupants keep between themselves and objects [3]. The boundary layer concept has been investigated by numerous researchers [7-10] who agree that the phenomenon occurs during evacuations.

Pauls studied 58 cases of total evacuation of high-rise office buildings to determine the boundary layer width commonly used within stairwells [8]. Each case pertained to one exit stairwell, so each building studied usually contained two exit stairwells, or two cases. Pauls’ analysis had two main components. The first involved a statistical regression analysis of the mean evacuation flow vs. the measured stair width of the 58 cases [8]. The other component involved “a graphical analysis of where individuals in a crowd locate themselves across the width of a stair used in high flow or capacity conditions” [8] using video footage of such situations from three stairs.

Pauls used two iterations of the regression analysis, with the second one taking into account different variables that could have an effect on flow, such as density, clothing worn, stair wall roughness, tread dimensions, building height, etc. [8]. He found that the regression line was a straight-line function that intercepted the x-axis at 300 mm [8]. The video analysis of the three crowded stairs also found that approximately 150 mm were unoccupied at each side of the stair [8], leading to a boundary layer width of 150 mm, or 300 mm for both sides, for a stairwell. This is the width given by Gwynne and Rosenbaum [3] and employed by the hydraulic model. For stairwells, the clear width is the measured tread width [3]. Figure 2-1 illustrates the measurement of the effective width of stairs in relation to the boundary layers due to walls, handrails, and seating.

As mentioned before, the three main parameters in assessing emergency movement in the hydraulic model are density, speed, and flow. Perhaps the most difficult parameter (yet most important) to quantify is density. Density is defined as the level of crowdedness in an evacuation route [3]. In the hydraulic model, density is the amount of people per unit area within the evacuation route. However, there are other ways of measuring density involving different units. These units include amount of people per unit space, the space available per person, and the proportion of floor space occupied [6].

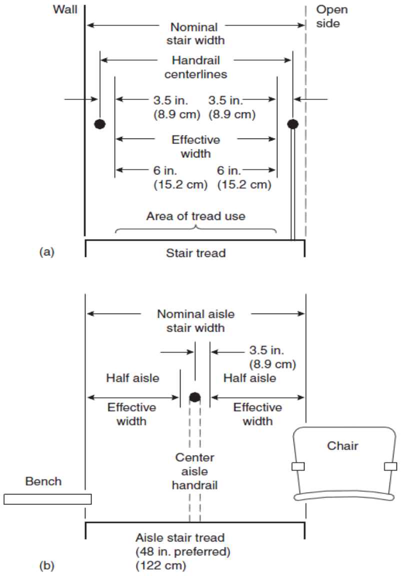


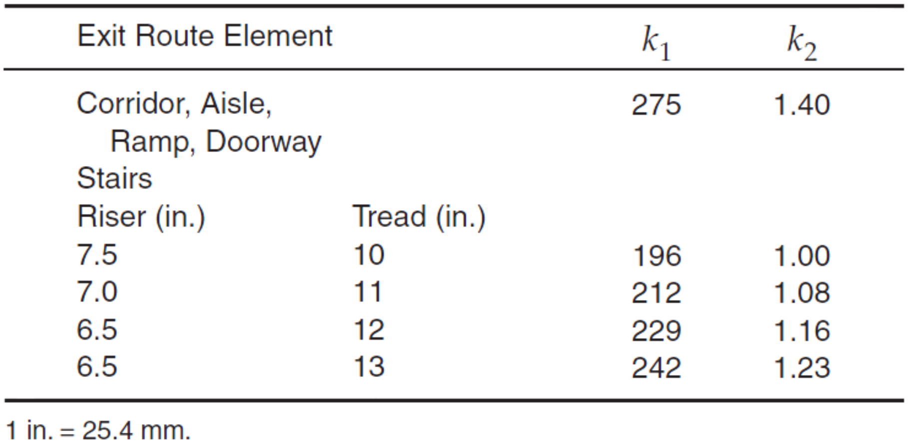
Figure 2-1: Measuring the Effective Width of Stairs [3, p. 3-378]

It has become a challenge for researchers to determine which method of measuring density is the most accurate and will obtain the best results. In her thesis, Blair stated that one of the factors that might have caused the significant amount of variation in speed and flow with respect to density within the high-rise stairwells that she studied (which are the same stairwells analyzed in this study) was the way that she calculated density [11]. The area that Blair used to calculate the densities was the area of tread and landing space from one camera to the next, which was usually the area between two flights of stairs. Also, Blair calculated the density of each occupant by counting the number of individuals in *front* of that occupant over the area of the two flights.

Another important parameter within the hydraulic model is speed. Speed is defined as the movement velocity of exiting occupants [3], or the amount of distance an occupant traverses the stair per time it takes that occupant to cover that distance. As stated before, numerous works have shown that the speed of a group or an individual within a group is affected by the population density [6, 7, 8, 9]. The more crowded an exit route is, the slower the individuals within that route will be able to exit. The following relationships that are used by the hydraulic model were derived from the work of Fruin [7], Pauls [8, 9], and Predtechenskii and Milinskii [6]. The model states that if the population density is less than 0.54 persons/m^2, then these are considered low-density situations and the occupants will move at their own pace [3]. High-density situations in which no movement can occur happen when the population density is greater than 3.8 persons/m^2 [3]. The model states that between the population density limits given above, the relationship between speed and density is assumed to be the following linear equation [3]:

$$\mathrm{S} = \mathrm{k} - \mathrm{akD} = \mathrm{k}(1 - \mathrm{aD}) \tag{2}$$

where S is the speed along the line of travel, D is the population density in persons per unit area, a is a constant equal to 0.266 when S is in m/s and D is in persons/m^2, and k is a constant depending on the riser and tread size for stairs and is given in Table 2-1 [3]. Note: k_1 is the constant used for English units and k_2 for metric.



Exit Route Element		k_1	k_2
Corridor, Aisle, Ramp, Doorway		275	1.40
Stairs			
Riser (in.)	Tread (in.)		
7.5	10	196	1.00
7.0	11	212	1.08
6.5	12	229	1.16
6.5	13	242	1.23

1 in. = 25.4 mm.

Table 2-1: Constant k for SFPE Speed Correlation [3, p. 3-379]

For stairs, the line of travel required for the measurement of S in equation (2) is along the line of the treads. This is essentially calculated using the Pythagorean Theorem, with the line of travel being the hypotenuse for each stair.

The specific flow can then be calculated in order to determine the calculated flow. The specific flow is defined as the flow of evacuees past a point in the exit route per unit time per unit effective width. The metric units of specific flow are persons/s/m effective width. The equation for determining specific flow is simply [3]:

$$F_S = S * D \tag{3}$$

where F_S is the specific flow, S is the speed, and D is the population density. Combining equations (2) and (3) yields:

$$F_S = (1 - aD) * kD \tag{4}$$

This specific flow can then be used to find the calculated flow by the following equation [3]:

$$F_C = F_S * W_e \tag{5}$$

where F_C is the calculated flow (predicted flow rate of persons passing a certain point in the exit route in persons/unit time), F_S is the specific flow, and W_e is the effective width of the route. Substituting F_S from equation (4) into equation (5) yields:

$$F_C = (1 - aD) * kDW_e \tag{6}$$

This flow rate can then be used to predict the time of passage required for a group of people to traverse an egress component:

$$t_p = \frac{P}{F_C} \tag{7}$$

where t_p is time for passage, P is the number of evacuees, and F_C is the calculated flow rate. The preceding equations together form the backbone of the hydraulic model of emergency human movement.

Because of the assumptions of the hydraulic model, it can be rather simplistic and consists of the following limitations:

“1. Behaviors that detract from movement are not explicitly considered.

2. The numbers of people in a structural component are considered rather than their identity and their individual attributes.
3. Movement between egress components is considered (e.g. from room to room), rather than within them.
4. The results are deterministic and will therefore remain the same unless changes are made to the scenario or the assumptions employed” [3].

Actual evacuations are not only affected by the egress component geometry and the density within that component, but also by the behaviors of the individual occupants and how they interact with each other and the surrounding environment. For this reason, the tendency in the hydraulic model is to provide “an optimistic estimate of evacuation time” [3]. The model does not account for human behavior factors that might increase overall evacuation time.

2.2 Computer Egress Models

There are currently many different computer egress models used in assessing emergency movement characteristics of evacuating populations. Some models are more sophisticated than others, but there is a push towards creating more sophisticated behavioral simulation models to account for the inherent limitations of the hydraulic model. Yet, because behavioral models are far more complex, there is a need for more current, sound evacuation data if the assumptions contained in these models are to be based on reality [12]. The current NIST study of the video recordings of the high-rise office building stairwells is part of an ongoing effort to obtain more raw data on evacuations to hopefully obtain better evacuation models that not only quantify speed, density, and flow, but also incorporate human behavior aspects.

While Section 2.1 deals with a manual engineering approach to modeling (the hydraulic model), this section deals with current computational modeling approaches used. As stated before, some computer models are more sophisticated than others, “ranging from a relatively crude account of homogeneous occupant flow to autonomous agents moving throughout three-dimensional space” [13].

A vital part in computer modeling is the selection of an appropriate model. Computer models must be understood by the user and be selected based on project deliverables, timing, funding, etc. Model validation is an important component of the selection process. Computer egress models are validated using different techniques including “validation against code requirements, validation against fire drills or other people movement experiments/trials, validation against literature on past evacuation experiments (flow rate, etc.), validation against other models, and third-party validation" [13]. The results and trends shown in the current study can hopefully be used by both computer model users and developers in validating computer models in question.

The three different types of modeling methods currently available are:

- Movement models: Concentrate on the simulation of occupant movement without a behavioral component.
- Partial behavior models: Primarily calculate occupant movement, but also simulate behavior to some degree.
- Behavioral models: Incorporate occupants performing actions in addition to movement to a specified goal [13].

The goal of this thesis is to provide trends to aid in the validation and development of behavioral models. By examining behavioral studies like this thesis, the level of refinement of populations, specifically the behaviors of populations can be developed and validated. Currently, the refinement of the population in computer models either represents the population as individuals (microscopic level) or as a homogeneous population (macroscopic level) [13]. Behaviors within computer egress models "can be defined by the user or model (deterministic) or based on probabilities specified by the user (stochastic)" [13].

The different ways that models simulate behavior include the following methods:

- "Neglect to simulate behavior
- Simulate only occupant characteristics that affect movement
- Simulate behavior conditionally (individuals are affected by conditions within the building)

- Allow behavior to emerge adaptively (attempting to simulate the decision-making process)” [13].

For some of the conditional behavioral models, it is common “that the user can specify certain behavioral actions for individuals or sometimes distribute certain probabilities of behaviors over a segment of the population” [13]. Thus, it is of utmost importance that “the conditions under which the actions are performed, the likelihood of their performance, and the consequences of their performance should be based on data” [13], such as the data trends presented in this thesis.

2.3 Social Groups vs. Physical Platoons

One of the behavioral aspects of evacuating occupants seen in the NIST data is the formation and dissipation of platoons (the term was first used by Pushkarev and Zupan [14]) within the overall flow. Pushkarev and Zupan explored the pedestrian travel demand of a section of the central business district in New York by observing human movement down several avenues and long streets. They found that “there is a considerable variation in pedestrian flow from instant to instant because of the phenomenon of platooning or bunching, which is caused to a large extent, by changes in traffic lights” [14]. Pushkarev and Zupan stated that “the short-term fluctuations due to platooning” [14] were a large source of error in their equations relating the presence of pedestrians to building use and walkway space. This platooning is directly analogous to the platooning observed in traffic flow theory due to traffic lights.

These types of platoons are called physical platoons because they are distinguished by their specific movement characteristics and are physically separated from one platoon to the next. Social grouping, on the other hand, involves groups distinguished by the social interactions of individuals within the group. It is typical for individuals within a social group to know each other, whereas individuals within a physical platoon may not know one another. Throughout the limited fire protection engineering literature on group movement during emergency situations, social grouping is described. Physical platooning, on the other hand, is described by the traffic literature from civil engineering. It is important to note that due to the behavioral limitations of the NIST data, platoons are identified and described in a physical manner within the high-rise stairwells in this thesis.

2.3.1 Social Groups in the Fire Protection Literature

Although many publications of emergency and/or drill people movement mention the phenomenon of social groups, none really explore the subject. The studies (i.e. Pauls [15], Pauls and Jones [16]; Kagawa et al. [17]; Jones and Hewitt [18]; Proulx [19]; Proulx et al. [20]; Bryan [4]; Latane and Darley [21];and Kratchman [22]) all mention groups evacuating in one way or another.

As mentioned in Section 2.1, Jake Pauls studied high-rise office building stairwell movement in Ottawa for both total and phased evacuation procedures in the 1970s. He mentioned that during total evacuation, “very high flows down stairs can be achieved only in very contrived situations involving specially motivated groups of individuals who temporarily disregard the normal need for personal space” [15]. He also stated that “there were often large single-sex groups in the streams of evacuees (partly as a result of the ‘ladies first’ procedure at the entries to exits)” [16].

Although phased evacuation somewhat forces the flow into groups of people from particular floors, total evacuation procedures also seem to contain platoons which are more or less formed due to the actions of a platoon leader (i.e. someone slower than the others due to disability, age, etc.), and the social interactions between people in a platoon. In civil engineering, traffic flow theory provides calculations concerning platoons formed by traffic lights (analogous to phased evacuation in high-rise stairwells), as well as those formed on a highway during dense conditions (analogous to total evacuation in high-rise stairwells). During phased evacuation, groups of floors are evacuated at specific times with those floors closest to the fire evacuating first. Thus, groups of vehicles moving through a green light are analogous to the groups of floors allowed to move first during a phased evacuation. On the other hand, a total evacuation allows all floors to evacuate the building at the same time. This can lead to more dense situations and possibly the formation of queues, analogous to traffic jams on a highway.

In 1985, Kagawa et al. [17] made observations of people movement in two stairwells within a 53 story office building in Tokyo during a fire drill evacuation. Kagawa et al. placed video cameras inside and outside of the doors to the stairwell to observe the flow of the evacuees in the stairwell and the mixing conditions occurring when multiple floors merged within the stairwell [17]. There was also a video camera placed on the first floor to observe the final outflow of the evacuees [17]. Several staff members carried video cameras or portable tape recorders while evacuating with the rest of the occupants. The paper mentions that “the flow of evacuating people came out in groups headed by their leaders,” [17] suggesting that platooning occurred. However, Kagawa et al. did not elaborate on the phenomenon, nor suggest why such an event happened.

Also in 1985, Jones and Hewitt described group formations and the role of leadership within these groups during a high-rise office building evacuation in Canada [18]. They interviewed some 40 occupants who had been involved with an actual fire evacuation that occurred in a 27 story office building in Ottawa. Four case studies were provided to explore the difference between “imposed” (authoritative) leaders and “emergent” (situational) leaders [18].

Jones and Hewitt stated that “imposed leadership is determined by authority or by virtue of a person’s position in the organizational hierarchy, whereas the situational approach conceives of leadership in terms of the function to be performed rather than in terms of the persisting traits of the leader” [18].

Case 1 involved a group of five individuals who followed the directions of their supervisor to use an elevator, which displayed a clear example of imposed leadership. Some of the members in the group admitted to knowing that the use of an elevator is not always the best course of action during a fire; however, they followed the supervisor’s instructions anyway, with one woman saying, “I just did what the boss told me” [18].

Case 2 displayed examples of both imposed and emergent leadership that caused a split in a group. The group was made up of one supervisor who first took charge and led the group to the nearest exit stairwell. During the descent, the group encountered smoke within the stairwell and had to turn back and decide on the best course of action. The supervisor suggested that the group should ascend the stairs to the roof where they could get some fresh air. Another man in the group, however, stated that since smoke rises, the best course of action would be to put damp clothing across their mouths and descend the remaining nine floors to the ground floor. This man was an example of an emergent leader, and some followed his advice, while others followed the advice of the supervisor (the imposed leader).

An imposed leader’s plan that failed was the topic of Case 3. The group from Case 2 that proceeded to the roof was met by another group who decided to follow the imposed leadership of the supervisor. Once the group arrived at the roof access door, they realized that the door was locked. The group then split up and started to descend the stairs to the ground floor in smaller groups. These smaller groups “descended with those with whom they were most familiar” [18].

Case 4 explored a scenario in which neither imposed nor emergent leadership existed among the evacuees. These individuals were mostly supervisors or those who were "used to making decisions on their own without consultation" [18]. In essence, these individuals did not have to form into groups with leaders who had to decide on the best course of action.

Jones and Hewitt concluded that "the presence of leadership and the form that it takes do affect the evacuation strategy adopted by a particular group" [18]. They maintained that although imposed leadership is usually followed based on the organizational hierarchy of the work place, people will follow such a leader only so far. If the imposed leader does not achieve the goal of the group, an emergent leader usually steps up to decide on a different course of action.

More recent findings on social grouping during emergency situations have been documented by Dr. Guylene Proulx [19]. Her observations are from an experiment designed to observe evacuation time and occupant movement in four apartment buildings during a fire drill. The apartment buildings were characterized as mixed occupancy buildings and located in four different cities [19]. The buildings were 6-7 stories tall containing between 80 and 130 apartments with an average population of 150 occupants [19]. Although the study did not contain very dense situations such as those seen in a high-rise building, it did provide important observations on platoon movement.

During each drill, the data was collected from 12 video cameras that recorded the time to respond to the alarm, the location, time, and frequency of movements, and the interactions between occupants [19]. Proulx identified two distinct groups of occupants called the "limitation" group and "no limitation" group based on their behavior during the evacuation. Within the "limitation" group, people characteristics were "that they walked with a cane, were slow walkers, were visually impaired, had multiple sclerosis, were carrying children, or were occupants over 65 years old who had no outward signs of impairment but who were likely to have some sort of limitation due to their age" [19]. Therefore, the "limitation" group was comprised of those occupants who could prolong the evacuation time of the population. Proulx stated that the occupants with limitations were slower on average than the non-limitation group for the time to start and the time to evacuate, but that these differences were not significant. The average time to move (i.e. the time from apartment exit to building exit) was, however, significantly different between the two groups. Proulx stated that "once people left their apartments, the stairs seemed to pose a problem for those with limitations and, as a result, they moved significantly slower than others" [19].

Proulx used the video camera footage to observe people movement in the stairwells of the four apartment buildings. Once again, the stairs were never crowded during the evacuation due to the relatively low number of occupants. Proulx found that among the occupants participating in the drills, small children between the ages of 2 and 5 and senior citizens (those over the age of 65) were on average the slowest to descend the stairs. The small children would usually descend holding the hand of a parent, while using their other hand to hold onto the handrail. Moving as such, the parent and small child would occupy the full width of the stairwell, which Proulx said "would have considerably slowed down the evacuation of other descending occupants if there had been a crowd on the stairs" [19].

During the evacuations of the four apartment buildings, Proulx stated that people travelled in groups. These groups were usually "pairs or groups of three" [19] mostly comprised of families. The families with small children were found to travel "in a close group with the adult carrying the smallest child" [19]. Proulx found that as children increased in age (age of 6 and older) the family groups would split slightly with the older child “usually four or five steps ahead racing down the stairs” [19]. Although some senior citizens travelled alone, most were found to travel in groups of two or three, as well.

Among the four apartment buildings, Proulx calculated that approximately 62% of the occupants evacuated in groups [19]. She also found that these group formations usually delayed the speed of the group because the “members tended to assume the speed of the slowest person” [19] (usually a small child or senior citizen).

Proulx conducted another study with Reid and Cavan in which they mentioned group formation during evacuation [20]. The human behavior study was based on the responses to a questionnaire given to occupants who had experienced an actual fire situation, specifically the Cook County Administration Building fire, which occurred on October 17, 2003 in Chicago, IL. The fire occurred on the 12th floor within the 36-story unsprinklered office building and resulted in six fatalities and a dozen injuries [20]. Of the estimated 223 occupants who were in the building at the time of the fire (5 p.m. on a Friday), 89 responded to the questionnaire survey [20]. Therefore, approximately 40% of the occupants in the building during the fire responded, which according to the authors was a good response rate.

According to the human behavior study of the Cook County Administration Building fire, 77% of the individuals who were in the building at the time of the fire were in a group when they started to evacuate [20]. Half of the 89 respondents reported that they waited for others before they began to evacuate [20]. Of those who left in a group, 28% left in a group of 2 persons, 39% left in a group of 3-5, 21% left in a group of 6-10, and 11% left in a group of more than 11, with two respondents reporting that they left in a group of 30 persons [20]. Figure 2-2 [20] illustrates the breakdown of individuals who began to evacuate in a group during the office building fire.

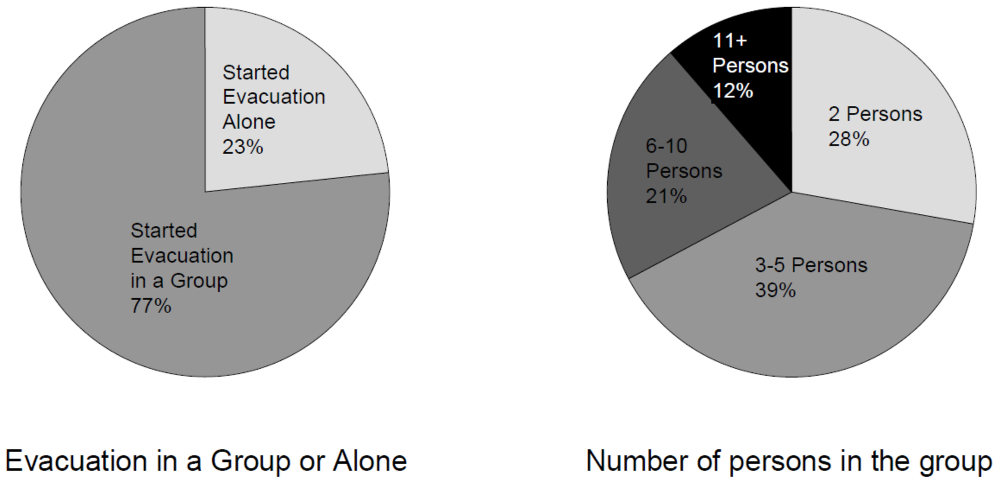


Figure 2-2: Social Interactions when Starting Evacuation [20]

Some papers have mentioned that the presence of a social group can in fact inhibit the overall egress performance of the population. J.L. Bryan stated, “the recognition of ambiguous fire incident cues as indicators of a possible emergency condition appears to be inhibited by the presence of other persons” [4]. In other words, the presence of a group of individuals can at times increase the pre-movement time of the individuals (thereby increasing the overall evacuation time) due to social interactions primarily regarding the emergency cues given and/or received. Also, Latane and Darley studied the effects of an emergency situation on college students and the inhibitions that can arise from the interactions among a social group [21].

One of the more recent papers pertaining to emergency stairwell movement where platoons were mentioned was Jessica Kratchman’s Master’s Thesis [22]. Kratchman investigated the effects of firefighter counter-flow on occupant descent in two stairwells of a six-story office building. The main finding of the thesis was that the typical parameters of speed, density, and flow for determining people movement were also largely dependent on human behavior, and not solely on one another. In her thesis, Kratchman recorded whether occupants traveled in social groups and characterized this as an adaptive behavior that “may not be considered to hinder evacuation, but it is important to note how people tended to travel” [22].

Kratchman also reported that “there were even cases where the occupants slowed down because they were socializing in the stairwell” [22], which is a clear indicator of a social group that hindered the overall egress performance.

Kratchman reported a situation in which a group of individuals made not only personal decisions during the evacuation, but group decisions as well. This led to a significant effect on the flow rate because the group performed a series of non-adaptive behaviors, such as the reentrance of the building during the evacuation [22]. Kratchman went on to report that “this group actually stopped on the stairwell landing to have a discussion both before and after re-entry (which blocked the stairwell for others), and as a group, they left the stairwell together” [22].

2.3.2 Physical Platoons in Traffic Flow Theory

In the civil engineering literature on traffic flow theory, vehicles are analyzed using either microscopic or macroscopic models to determine highway capacity and traffic jam scenarios. These traffic models are grouped into four distinct families based on the kind of mathematics used in each:

1. “Cellular automata (and car-hopping) models: based on a set of simple short range interaction rules among vehicles.
2. Car-following (and follow-the-leader, and optimal velocity) models: based on ordinary differential equations, in a framework close to that of Newtonian mechanics.
3. Kinetic models: start from some pre-assigned set of (generally pairwise) interaction rules and obtain the system description from a stochastic point of view.
4. Continuous models: similar to those of hydrodynamics, based on the description of quantities that are of macroscopic nature” [23].

These traffic flow models are similar to the computer egress models used in emergency human movement in their population and behavioral levels of refinement. As with the computer egress models, there currently is a push towards a more individualistic representation of vehicles in traffic flow models. More realistic representations of traffic flow must not neglect the differences in vehicle classes and driving attitudes [24, 25], just as more realistic representations of emergency human movement must not neglect differences in human behavior.

Microscopic models (kinetic models) are usually more complex than macroscopic models because they explore interactions between individual components and consider different driver behaviors. The kinetic model is based on the Boltzmann equation and treats vehicles as gas particles [26]. The microscopic state of vehicles is identified by a dimensionless position and velocity of each vehicle based on defined characteristic variables. In kinetic theory, the "derivation of evolution equations needs the modeling of pair interactions at the microscopic level" [26]. Using the Boltzmann equation, localized interactions are distinguished when both vehicles are at a minimal distance. The microscopic model provides a framework for determining how different vehicles/drivers (analogous to evacuees/walkers) affect the flow by "assuming the specificity of drivers is related to a certain random variable ω in a suitable domain D_ω linked to a suitable probability density $P(\omega)$" [26]. However, the complexity of the microscopic model, and the limited amount of sound behavioral data currently in the evacuation field make kinetic egress modeling infeasible at this time.

The macroscopic model, also known as a hydrodynamical model, in traffic flow theory is similar to the hydraulic model in egress analysis. The same parameters (i.e. speed, density, flow) studied in people movement are described in the macroscopic model of traffic flow theory. The macroscopic model is a “continuous model based on the description of quantities that are of macroscopical nature” [23].

Unlike the majority of past stairwell evacuation research, research and models have been conducted involving platoon traffic flow. One such model is known as the Greenshield’s model and is used throughout a paper exploring platoon dynamics upstream and downstream from a traffic light [27]. This paper, along with others, observes the dispersion and compression of platoons due to the formation of shockwaves stemming from queues. It is shown that “compression does not only occur to platoons entering the link in red but also to those entering in green even in the absence of a downstream signal” [27]. The basic platoon modeling is macroscopic and based on the shockwaves created by the traffic lights. Though the queuing and shockwaves at traffic lights are artificially created, similar queuing and shockwaves are created due to jams in high-rise stairwells during total evacuations.

In traffic flow platoon analyses it is shown that platoons tend to elongate when entering areas of lower density and, conversely, at higher densities they are compressed [27]. Platoons in traffic flow are typically loosely defined as any arbitrarily specified group of vehicles. These platoons are usually physically separated by a distance, such as a the distance separating a platoon of vehicles going through a green traffic light from a platoon stopped by a red traffic light at the same signal [27]. A similar physical representation of a platoon is used to identify platoons in the current paper. Platoons are distinguished by the distance from one platoon to the next and differing flow patterns, such as elongation or compression (similar to patterns observed in traffic platoons).

2.4 Merging Behavior in the Fire Protection Literature

Several papers have been published regarding merging behavior at the stair/floor interface on landings within stairwells. Some papers were written in the 1980s and provide more qualitative findings on the phenomenon, while more recent papers have explored the effects of merging quantitatively. It has been found that merging occupants entering stairwells at their floor of origin influence the speed at which both the floor and stair streams can be evacuated in high-rise buildings [28]. Because merging of stair and floor occupants is common during building evacuations [17, 28-32], a detailed study of the event and how it impacts the evacuation flow is critical in assessing evacuation times of occupants within these buildings.

In 1985, Hukugo et al. conducted three experiments exploring the merging of about 150 occupants within stairwells [29]. The different experiments were categorized based on which stream of occupants established their movement flow first. The first experiment examined the effects of merging when the stair stream started first, while the second experiment examined merging effects when the floor stream started first. The third experiment investigated the merging process when both the stair and the floor streams began evacuation at the same time. Hukugo et al. reported that when both the floor and stair streams established themselves at the same time (experiment 3), the flow rate into the landing merger region was biased in favor of the floor (by an average of 60%) [29]. When either the floor or stair streams were allowed to establish flow first, the authors found that the flow into the merger region was split 50:50 between stair and floor occupants [29].

Takeichi et al. found that landing/door/ stair geometry and density play a role in the flow rates of the floor stream [30]. When the density within the stairwell was relatively low, Takeichi et al. stated that the floor flow rate onto the landing increased [30]. Also, the authors found that when the door leading into the landing was located adjacent to the incoming stair, the floor flow rate increased [30]. Another key finding that they noted was that the floor flow rate decreased when the landing door was initially closed [30]. It should be noted, however, that the experiments of Takeichi, et al., only involved some 27 people, and that the density of the individuals was artificially increased during the test. This led to brief periods of merging, and may not reflect what could occur during actual evacuations.

When Pauls did his evacuation analyses of high-rise buildings in Canada during the late 1960s and early 1970s, he reported deference behavior between the stair and floor streams at the landing/stair interface [31]. His findings were based on observed occurrences of the merging process, but did not offer any quantitative results. Pauls reported that there was a “fairly consistent” pattern where the stair stream deferred to the floor stream during merging [31]. He also stated that the merging process can greatly reduce the movement speed of the stair occupants on higher floors in high-rise buildings, and that as the stair load increases, complete flow stagnation (queues) of increasing duration for higher floors was bound to occur [31].

Flow stagnation caused by the merging of multiple floors in a high-rise stairwell was also reported by Kagawa et al. [17]. Around 30% of the individuals in the study stated that they slowed down or stopped at least once during their descent [17]. Kagawa et al. discussed that the merging of multiple lower floors was a factor in the queuing of stair occupants descending from the upper floors. The authors stated that “during the mixing of people’s flow on the landings, there may arise a standstill on either side to let the others go forward” [17].

One of the most recent papers on merging behavior within stairwells was published in early 2011. Boyce et al. [32], observed the merging process in stairwells of three different types of buildings (two university buildings and one health center) that contained differing stair/door/landing geometries. The authors used merge ratios where they counted the number of occupants descending from the stair compared with the number of occupants coming in from the floor at the merge region to determine which stream was favored. The merge ratios were able to quantitatively determine which stream was favored during 20 s time periods from the beginning of sustained merging in the stair [32]. For the analysis, the authors used video cameras set up in adjacent landings within the stairs to count the stair and floor occupants that passed an imaginary line that dissected the landing and was perpendicular to the stair flow, which they called the limit of the merging region [32]. Once a floor occupant passed this line, they were considered to have merged and were part of the stair flow. The main finding of the paper was that within stairwells where there was an extended period of sustained merging, the overall merging ratio was split 50:50 between the stair and floor occupants despite differing stair/landing geometries and differing stair/door widths [32].

In the two university building stairwells, there were differing landing door positions, with one containing a door adjacent to the incoming stair (study 1) and one containing a door opposite the incoming stair (study 2). Figures 2-3 and 2-4 show the landing configurations with the locations of the landing doors for study 1 and study 2, respectively. Although both overall merging ratios during the entire period of sustained merging were approximately 50:50, study 1 contained merge ratios that varied over the duration of the merge, while study 2 had little variation over the duration [32]. During the early stages of merging in study 1, the stair stream took priority, but as time went on, the floor stream began to take priority, especially at higher stair densities [32]. The authors suggested that this variation in the merge ratios might be due to the reduced stair movement just after the merge, but that further research is needed in this area of study. In study 2, the authors suggested that because the door was located opposite the incoming stair, this “facilitated a more natural filter of persons from the floor,” [32] which in effect led to little variation in the merge ratios.

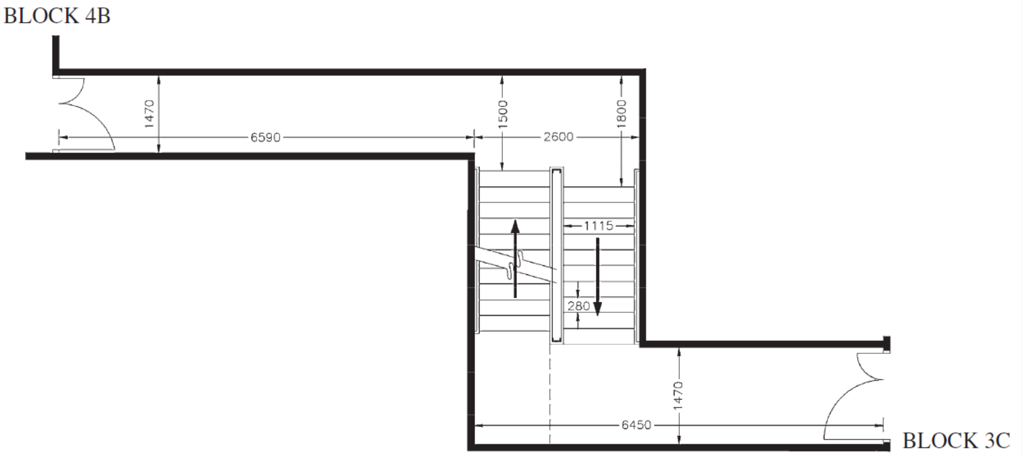


Figure 2-3: Stair and Landing Door Configuration and Dimensions of Study 1 [32]

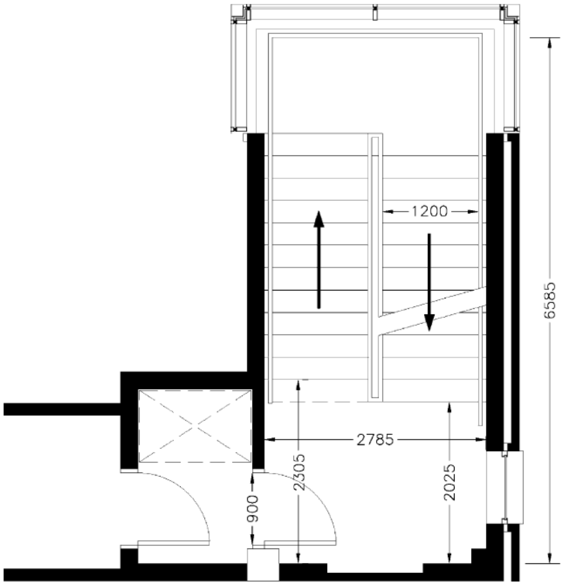


Figure 2-4: Stair and Landing Door Configuration and Dimensions of Study 2 [32]

The study 3 (health center) stairwell had little sustained merging, so a merge ratio analysis was not done. However, Boyce et al. reported two instances in which obvious deference behavior was exhibited by the stair stream [32]. At one point during the evacuation, three occupants carrying babies were given priority by the stair stream [32]. In another instance, a man descending the stair stopped to let five women enter the stair and begin their descent before him [32]. The authors reported that due to their uniforms, the females were all employees at the health center, and that the man probably worked for the center as well, and knew the women. The authors suggested that deference behavior could be linked to gender or role within a work place, but that further research was needed to assess the validity of this assumption [32].

2.5 Validity of Fire Drill Experiments

One of the main issues that some individuals in the fire protection research community have regarding emergency people movement is the validity of data that is extracted from fire drills. Some individuals within the emergency egress research community believe that because the data does not come from actual fire emergencies, the results stemming from such research should not be used to make conclusions blindly. While it is true that fire drills do not involve actual fire scenarios, research has shown that human behavior during unannounced drills is comparable to human behavior during actual fire events, especially in high-rise buildings [2]. During actual fire events in high-rise buildings, the majority of the building population does not experience direct fire cues, such as actually seeing the fire or smelling smoke. Therefore, these occupants are assumed to act just as they would act during an unannounced fire drill, since they are not certain whether it is an actual emergency or not. Because the four high-rise office buildings in this study had unannounced fire drills, it is assumed that the occupants reacted just as they would have had it been an actual fire event.

In Dr. Proulx's chapter on evacuation time in The SFPE Handbook, 3rd Edition, she summarizes some aspects of people movement in tall buildings based on multiple research sources on the subject [33]. She presents the following list:

> "1. Panic is very rare even in fires. Normal patterns of behavior, movement route choices, and relationships with others tend to persist during emergency situations.

2. People's behavior tends to be altruistic and reasonable, especially in light of the limited and often ambiguous information available to people at the time of the event.

3. After perceiving a fire cue, such as the fire alarm signal or smelling smoke, people often ignore these initial cues or spend time investigating, seeking information about the nature and seriousness of the situation, which creates a delay time before starting evacuation movement.

4. Faced with ambiguous information and short time for decision making, people are likely to apply a well-run decision plan when choosing an evacuation route, consequently moving toward their most familiar way out of the building.

5. Evacuation, and response to fire generally, is often a social response; people tend to act as a group and to attempt to evacuate with people with whom they have emotional ties.

6. Problems that are encountered during normal building use will tend to persist and exacerbate situations in emergencies. Included are faulty communication, circulation hazards, wayfinding problems" [33].

The aspects of people movement during emergencies highlighted above demonstrate how use of unannounced drill data can be a good predictor of how the population will move during an actual fire event. Although many civilians and even some fire protection engineers believe that panic is common during fire, research has shown that this is not the case. In the majority of fire events, occupants are shown to be collected as they make their way towards safety. Therefore, there is no reason to assume that the population would react more quickly during an actual emergency compared to an unannounced drill.

Chapter 3: Building Occupant Egress Data

The following chapter describes the high-rise buildings that the egress data was collected in for the current study, as well as the egress data and collection methods employed. First, a description of each of the buildings from which data is extracted is provided. The number of stories, stair widths, number of occupants, percentages of occupants that are male, female, or unknown, location of cameras, and general location of the buildings are used to describe each building analyzed. Then, the type of data and the method by which this data is collected are presented.

3.1 Description of Buildings

NIST collected data from 13 office and residential buildings across the United States ranging from 6 to 62 stories in height [34]. As of December 2009, NIST released egress data from four of the 13 buildings. Each of these four buildings is classified as high-density, high-rise office buildings. The four buildings from which data were released are Building 4, Building 5, Building 7, and Building 8. The stairwells within Buildings 4 and 5 are the stairwells that will be analyzed in the current study because the data within these buildings contained significantly different flow patterns. The following table represents an overview of different aspects of each building used in the study.

Building	Floors	Stair Width (m)	Occupants	% Male	% Female	% Unknown
4	24	1.12	594	52	46	2
5	10	1.27	793	53	42	5

Table 3-1: Overview of Different Building Aspects

3.1.1 Description of Building 4

Building 4 is a 24 story office building located on the west coast of the United States. There are two stairwells observed in Building 4 labeled as stairwell 4A and stairwell 4B. Stair 4A exits to the 2nd floor lobby where occupants must travel across the lobby to the building exit, while stair 4B exits directly to the outside on the first floor [34]. Both stairwells are 1.12 m wide (1.02 m between handrails) as measured by NIST [34]. Also, the measured riser height and tread depth of each step in each stairwell is 0.18 m by 0.28 m [34].

The evacuation drill of Building 4 occurred during the spring months of 2008 before lunch during normal business hours. There were 605 occupants who took part in the unannounced full building evacuation drill (249 in 4A and 356 in 4B) [34]. During the drill, stair 4A experienced counter-flow due to three firefighters traveling up the stairwell to the 13th floor approximately 1.5 min into the drill [34].

NIST set up video cameras in 19 different locations within the two stairwells in Building 4. For stair 4A, a total of 11 cameras were placed in the stair starting from the exit floor at floor 2 and then located on every other floor up to floor 22. For stair 4B, a total of 8 cameras were placed at the exit floor (labeled P1) and floors 4, 6, 10, 14, 16, 18, and 22 [34]. Most of the camera views for Building 4 show the main landing, as well as 2-3 steps leading to the main landing and 3-4 steps leading away from the main landing [34]. The number of steps leading to the main landing and away from the main landing varied slightly on different floors due to differences in the viewing angles of some cameras. A typical scene of the wide camera angle view where 3 steps can be seen leading to the main landing and 4 steps leading away is shown in Figure 3-1 [34].

Figure 3-1: Building 4 Typical Camera View [34]

3.1.2 Description of Building 5

Building 5 is a 10 story office building located on the west coast of the United States. There are two stairwells observed in Building 5 labeled as stairwell 5A and stairwell 5B. Both stairwells exit directly to the outside on floor 1 and are 1.27 m wide (1.22 m between handrails) as measured by NIST [34]. Also, the measured riser height and tread depth of each step in each stairwell is 0.18 m by 0.28 m [34].

The evacuation drill of Building 5 occurred during the spring months of 2008 before lunch during normal business hours. There were 804 occupants who took part in the unannounced full building evacuation drill (436 in 5A and 368 in 5B) [34]. During the drill, stair 5B experienced counter-flow due to six firefighters traveling up the stairwell to the 7th floor approximately 8 to 11 min into the drill [34].

NIST set up video cameras in 10 different locations within the two stairwells in Building 5. For both stairs 5A and 5B, 5 cameras were placed every other floor starting from the exit floor at floor 1 up to floor 9 [34]. Most of the camera views for Building 5 show the main landing, as well as 3-4 steps leading to the main landing and 4-6 steps leading away from the main landing [34]. The number of steps leading to the main landing and away from the main landing varied slightly on different floors due to the different camera angles of some cameras.

A typical scene of the wide camera angle view where 4 steps can be seen leading to the main landing and 6 steps leading away with the exit point is shown in Figure 3-2 [34].

Figure 3-2: Building 5 Typical Camera View [34]

3.2 Egress Data Collected by NIST

As previously mentioned, NIST collected egress data of high-rise evacuation drills in office buildings through use of video cameras at certain floors within the egress stairwells. The overhead camera placement (Figures 3-1 to 3-2) within the exit stairs gave a view of the main landing as well as steps leading to and away from the main landing. This placement allowed for those at NIST to determine the times when each occupant was seen entering and exiting the camera view on each particular floor.

After video footage was collected from each stairwell during each building evacuation drill, NIST recorded specific data from the videos into a spreadsheet format in Excel. For each stair, data were collected for 1) each occupant evacuating in that stair and 2) each time during the drill that the occupant was seen at a specific floor in the stair (each camera position) [34].

The data collected for each occupant during the evacuation drill includes: occupant number, gender, floor of origin, whether he or she was carrying anything (Yes, No), his or her body size (less than ½ the stair, more than ½ the stair, or exactly half), whether he or she was alone or in a group during the drill, whether he or she was helping someone during the drill, and the floor on which he or she was first seen [34].

The occupant number assigned to each individual is based on the order in which they exited the building to aid with tracking purposes. So, occupant 1 is the first person to exit the entire stairwell, occupant 2 is the second to exit and so on. It is important to note that the passing behavior of individuals can be determined using the numbers assigned to occupants. For example, if occupant 5 is behind occupant 9 on Floor 5 of a stairwell, it can be determined that occupant 5 at some point between Floor 5 and the exit floor passed occupant 9.

The data collected each time an occupant was seen on a specific camera included the following: the time that he or she was seen entering the camera view, the time that he or she was seen exiting the camera view, his or her location on the stair (traveling on the inside, outside, or the middle of the stair), and his or her handrail usage (using the inside or outside handrail, or both of them at the same time) [34]. Because of the transient behavior of both the encumbrance data and the data involving handrail usage, these two sets of data were not used in this study. These two sets of data were considered to contain substantial error due to the subjective nature associated with differing NIST staff members extracting the data from the video to the spreadsheet [35]. The exit and enter times of each occupant are, however, used extensively in the study to aid in the identification of platoons, identification of passing and merging events, to approximate local descent times (inversely proportional to local movement speeds), to approximate flows, and to approximate local densities of individuals as seen in Chapter 4.

Chapter 4: Data Analysis

Chapter 4 explains how the data within the spreadsheets produced by NIST [34] are used to determine key movement parameters (i.e. descent times, movement speeds, flows, and densities), as well as how the data is used to identify groups and merging behaviors. As with the data used by Blair [11], the enter times and exit times of each occupant seen on each landing are synchronized to the correct time according to when the alarm sounded. This is done by simply subtracting each enter time and exit time by the time when the alarm sounded on that particular floor, so that time t =0 is the time when the alarm sounded. All times given in this report are with respect to this alarm initiation time.

4.1 Calculation of Descent Times

Local descent times of each occupant are calculated using the exit times from camera to camera. The locations of these exit points within the stairwells are shown as the red lines in Figures 4-1 and 4-2 for buildings 4 and 5, respectively. These points are simply where the occupant is last seen on camera for that particular floor. To calculate the local descent times, the camera exit time from the upper floor is subtracted from the lower camera exit time. For example, if Occupant 10 exits the camera view on floor 4 at 35 s and exits the camera view on floor 2 at 50 s, their descent time from floor 4 to floor 2 is simply:

$$t_{4\text{-}2} = 50\text{ s} - 35\text{ s} = 15\text{ s}$$

Using these local descent times, local movement speeds are estimated using the calculation in Section 4.2.

Figure 4-1: Exit Point in Stairs in Building 4

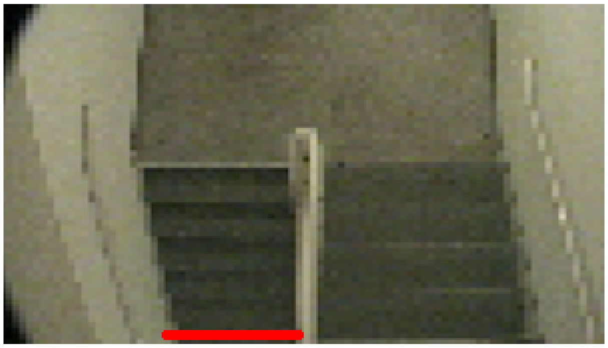


Figure 4-2: Exit Point in Stairs in Building 5

4.2 Calculation of Local Movement Speeds

Local movement speeds of each occupant were calculated for their travel between the exit points of two consecutive camera views. This was done by using the distance from each camera to the building exit, and the exit times at each landing with a camera.

NIST measured the distance from each camera exit location to the building exit (assumed to be at the bottom of each stairwell), and provided this information in each spreadsheet. Blair [11] calculated the distance along the slope of the stairs from camera exit location to the building exit using stair geometry concepts introduced by Predtechenskii and Milinskii [6] to determine whether the measurements provided by NIST were accurate. She found that the stair geometry calculations obtained distances that were in good agreement with the distances provided by NIST. Therefore, the distances provided by NIST were used to determine local movement speeds.

To determine the distance from one camera exit to the next, the distance from the lower floor exit to the building exit was subtracted from the higher floor exit to the building exit. For instance, if the distance from the exit at floor 22 to the building exit is given as 224 m, and the distance from the exit at floor 20 to the building exit is given as 202 m, then the distance from the exit at landing 22 to the exit at landing 20 (i.e. from camera to camera) is:

$$224\text{ m-}202\text{ m}=22\text{ m}$$

If an occupant's descent time is calculated as 20 s, the movement speed from the camera at floor 22 to the camera at floor 20 for this occupant is simply:

$$\text{S}=\frac{\text{distance traveled}}{\text{change in time}}=\frac{22\text{ m}}{20\text{ s}}=1.1\text{ m/s}$$

4.3 Calculation of Density

Rather than calculate density based on an area of stairs and landings from one camera to the next (method used by [11]), the local density of each occupant is determined based on the area of the landing and stairs within camera view. The measurements entitled "landing area" in the NIST spreadsheets are the measured areas of the landing and stairs within the camera view for each particular camera [35]. These measured areas are, therefore, used to calculate the local densities.

The number of occupants in the camera view when a particular occupant enters and exits are obtained to calculate the local densities of each occupant. Two counting algorithms are created in MATLAB to accomplish this (the algorithms are presented in Appendix A). One algorithm counts the number of people in the camera view when a particular occupant enters, and the other counts the number of people in view when a particular occupant exits. The input file necessary (entitled "Data" in the codes in Appendix A) contains two columns for enter and exit times of each occupant at each floor that has a camera. Column one in the code contains enter times and column two contains exit times for each occupant. Using these enter and exit times, MATLAB counts the number of people within the camera view for each occupant using a nested for loop, so as not to double count individuals. Also, the code was written to include the particular person in the count. For example, if a person enters the camera view when no one else is in view, the number of people counted in the code would be 1, not 0.

Two different densities are calculated for each occupant. One contains the average of both the enter and exit counts, while the other just involves the enter count. Using the average number of people when an occupant enters and exits a particular camera provides for an estimation of density based on the number of people around the occupant, and is the density used within the SFPE Handbook [3]. Alternatively, using just the number of people in view when an occupant enters a particular camera provides for an estimation of density based on only those people in front of the occupant.

Using both the average number of occupants seen on the camera view and the area given by NIST, an estimation of the local density surrounding an occupant can be calculated:

$$\mathrm{D}=\frac{\text{Average Number of Occupants}}{\text{Area Seen on Camera}}$$

For example, if the view area on the second floor is 3.8 m^2, and a certain occupant enters the camera view on the second floor with 3 occupants in view and exits the camera view on the second floor with 2 occupants in view, then their average local density is:

$$\mathrm{D}=\frac{\left(\frac{(3+2)}{2}\right)}{3.8}=\frac{2.5}{3.8}=0.66\ \text{persons}/\mathrm{m}^2$$

Using just the enter count to determine density, this same occupant would have a density of:

$$\mathrm{D}=\frac{3}{3.8}=0.79\ \text{persons}/\mathrm{m}^2$$

This calculation assumes that only those in front of the particular occupant have an effect on that occupant’s speed.

4.4 Calculation of Flow

Since the calculated flow is defined as the flow rate of people passing a certain point in the exit route in persons/unit time [3], flows will be calculated by counting the number of individuals passing either the enter point or the exit point and dividing by the amount of time it takes the individuals to pass that point.

For the flow analysis, both inflow (flow of people entering the camera view) and outflow (flow of people exiting the camera view) are calculated using the enter and exit times of occupants. The enter and exit times used to calculate the flows are with respect to the first person within the flow. So, the first person in the flow will have an enter and exit time of 0 with the times of the following occupants calculated with respect to that first person’s time.

Flows are calculated at specified time intervals based on the exit times. Therefore, if the inflow and outflow of occupants from 0 s to 10 s are desired, only occupants who exit the camera from 0 to 10 s are considered. The outflow is calculated by taking the number of occupants who exit the camera between 0 and 10 s and dividing this by the difference between the exit time of the first occupant and the last occupant in the 0 to 10 s interval. To calculate the inflow of these occupants, one must backtrack to the enter times of the specific occupants in question. The first and last occupants to enter from these individuals are used to calculate the inflow by counting the number of people entering from the first to the last and dividing by the difference between the enter time of the first and last occupant.

As an example, consider the inflow and outflow of floor occupants are from the time interval 0 to 6 s on floor 1 of a stair. Table 4-1 shows the enter times and exit times of the occupants who exit between 0 and 6 s for floor 1. The occupants are arranged in both enter order and exit order on the 1st floor camera. From the times displayed in Table 4-1, the outflow is

Enter Order	Enter Time (s)	Exit Order	Exit Time (s)
8	0	8	0
9	1.33	9	1.4
10	2.73	10	2.83
15	4.4	15	4.5
23	5.63	22	5.72
22	5.74	23	5.8

Table 4-1: Inflow and Outflow Example

calculated as:

$$F_{out}=\frac{6\ \text{persons}}{(5.8\text{-}0)\ \text{s}}=1.03\ \frac{\text{persons}}{\text{s}}$$

The inflow is calculated as:

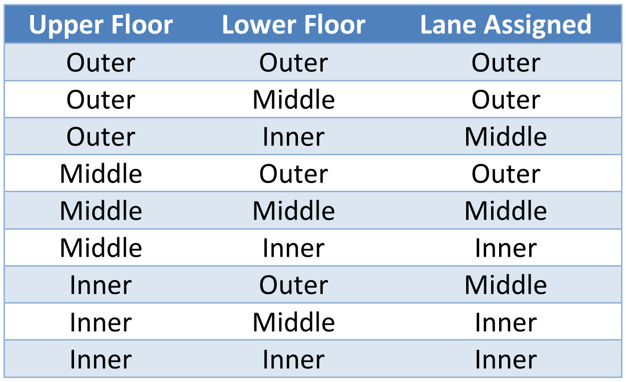
$$F_{in}=\frac{6\ \text{persons}}{(5.74\text{-}0)\ \text{s}}=1.05\ \frac{\text{persons}}{\text{s}}$$

Again, the enter and exit times in each flow analysis is with respect to the first person in the continuous flow. As the preceding example shows, at times, the order of occupants may change between the enter and exit. It is important to account for this and calculate the inflows and outflows based on the correct enter and exit orders of the occupants in question.

It is also important to note that the specified time intervals used to calculate the flows may be different. This is due to the lack of data containing continuous flows stemming from both the stair and the floor. Continuous flow is defined as flow of more than one person from the stair and more than one person from the floor. Because continuous flows occur at differing time intervals in the camera views within the differing sections of the different stairwells, the specified time intervals may vary.

4.5 Exit Lane Identification

Exit lanes are identified as the inner, outer, and middle lanes within the stair. By his lane identification method, Hoskins found that the majority of occupants within the section he analyzed traveled in the inner or outer lanes, with relatively few traveling in the middle lane [36]. Because only lanes of occupants are given at camera locations, Hoskins creates a method to identify the probable lanes in which the occupants travel between the floors in question. Hoskins classifies occupants as being in the inner, outer, or middle lanes based on the lane designation at the exit of the upper floor and the entrance of the lower floor as shown in Table 4-2 [36]. The lane assignment method employed by Hoskins is used in the current study to classify occupants as being in the inner, outer, or middle exit lanes.



Upper Floor	Lower Floor	Lane Assigned
Outer	Outer	Outer
Outer	Middle	Outer
Outer	Inner	Middle
Middle	Outer	Outer
Middle	Middle	Middle
Middle	Inner	Inner
Inner	Outer	Middle
Inner	Middle	Inner
Inner	Inner	Inner

Table 4-2: Lane Assignment Method by Hoskins [36]

4.6 Data Involving Queues

Without direct access to the evacuation video footage, two techniques were established to determine when and where queues occurred within the stairwell. Here, a queue is determined to have occurred when there is a statistically significant slowing of individuals, or complete flow stagnation. Queues occurred across multiple floors in the stairwells of both Buildings 4 and 5 [35]. Many [5, 17, 28, 31] have speculated that the high number of occupants and the merging process at the stair-floor interface are important factors that lead to queues in stairwells of total high-rise evacuations. These queues may in part be caused by stop-go phenomena as described by Pauls [31] and Kagawa et al. [17] where the stair population defers to the floor population, often coming to a complete stop to let the floor occupants merge. These queues can have a significant and unpredictable impact on the local movement speeds, which is why data affected by queues will not be used in the current data analysis if the intent is to predict movement speeds.

4.6.1 The Density Filter

One of the methods used to predict where and when queues occur in the data, is the creation of a density filter. The assumption is that above a certain critical density, a queue occurred or one was imminent. A determination of where queues occurred on camera and the occupants affected by the queues was established [36]. The calculated average densities of these individuals were then used in a two-sided statistical t-test to determine a 95% confidence interval for the critical density where queuing occurs. Results of the t-test indicated that the 95% confidence interval for the critical density in Building 4 was $1.40\,\frac{\mathrm{persons}}{\mathrm{m}^2} \leq \mathrm{D}_{\mathrm{critical}} \leq 1.88\,\frac{\mathrm{persons}}{\mathrm{m}^2}$, and in Building 5 was $1.23\,\frac{\mathrm{persons}}{\mathrm{m}^2} \leq \mathrm{D}_{\mathrm{critical}} \leq 1.32\,\frac{\mathrm{persons}}{\mathrm{m}^2}$. Therefore, any occupant with a calculated local average density greater than or equal to 1.40 persons/m^2 in Building 4 and 1.23 persons/m^2 in Building 5 were assumed to be affected by a queue at that section of the stair. Because these critical values will have some false positives, true negatives (or both), the camera view times and the off camera view times of each occupant were also used in the determination of occupants affected by queues.

4.6.2 Camera View Times and Off-Camera Times

To help determine the segments of the stairwell where queuing occurred, plots of the amount of time occupants spent within camera view and off camera were used. These plots helped to validate the density filter critical values obtained from the technique described in Section 4.5.1. The plots were also used to determine the occupants who stopped or slowed their descent when the local density was below the critical value found by the t-test. For each floor that contained a camera, each occupant's enter time was subtracted from their exit time to calculate the time they were seen on the landing/stair view area. The assumption is that when there is a noticeable upward spike in the camera view time data, the particular occupant experienced either slowing of movement or a movement stoppage caused by a queue. Figure 4-3 shows floor 7 from stairwell 5A, where a clear example of this upward spike in the camera time data can be seen.

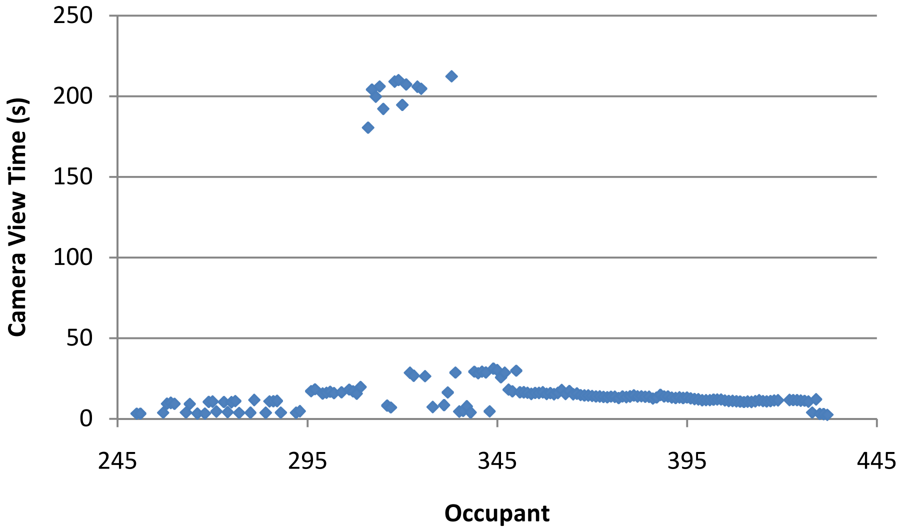


Figure 4-3: 5A, Floor 7 Camera View Time vs. Occupant

As Figure 4-3 shows, there is a definite spike in the data occurring between occupants 311 and 333. During this segment of the evacuation on floor 7, the camera view times for the majority of these occupants (those descending from upper floors) spiked to approximately 200 s. Thus, being these descending stair occupants were in the camera view for over three minutes, they were assumed to have stopped due to a queue. Before the queue reached the occupants on the seventh floor, the camera view times ranged from 3 to 20 s. Once occupants 311 to 333 were affected by the queue, their camera view times increased up to 10 times that of the occupants descending before the queue. Directly following queue dissipation, descending stair occupants had camera view times of approximately 30 s, which gradually decreased as time progressed. Plots of camera view time vs. occupant can be found in Appendix B for all four stairwells analyzed.[1]

In addition to camera view times, plots of times in which occupants are off camera are used to determine where occupants slowed or came to a stop in the stairwell between cameras. These times are labeled in the graphs as the floor in which the occupant just came from. So, floor 9 gives the off camera times of occupants between the exit point of floor 9 and the enter point of floor 7. Figure 4-4 shows the off camera times of occupants between the exit point of floor 9 and floor 7 in stairwell 5A.

The figure shows that occupants 322 and 339 through 396 spent the longest time in between landing 9 and landing 7. During the evacuation drills, occupants are not seen the majority of the time; therefore, one expects these times to be greater than the camera view times shown in Figure 4-3. From Figure 4-4, occupants 322 and 339 through 396 were affected by the same stoppage as occupants 311 through 333 were on camera in Figure 4-3. The difference between the two groups is hypothesized to be due to their position on the stair when the queue started. Occupants 311 through 333 were within camera view on floor 7, while occupants 322 and 339 through 396 were behind off camera between floors 9 and 7. Again, graphs of these times are found in Appendix B for all stairwells.

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[1] Some camera view times are excluded from these plots because they were clearly marked as safety officers on the spreadsheets and were clear outliers in the data set. For example, in stairwell 5A floor 5, the last occupant is recorded as wearing a yellow safety vest in the spreadsheets. This individual entered the fifth floor landing with no one else on camera and spent 179.9 s in camera view. The data point is an obvious outlier and does not reflect typical occupant movement during an evacuation.

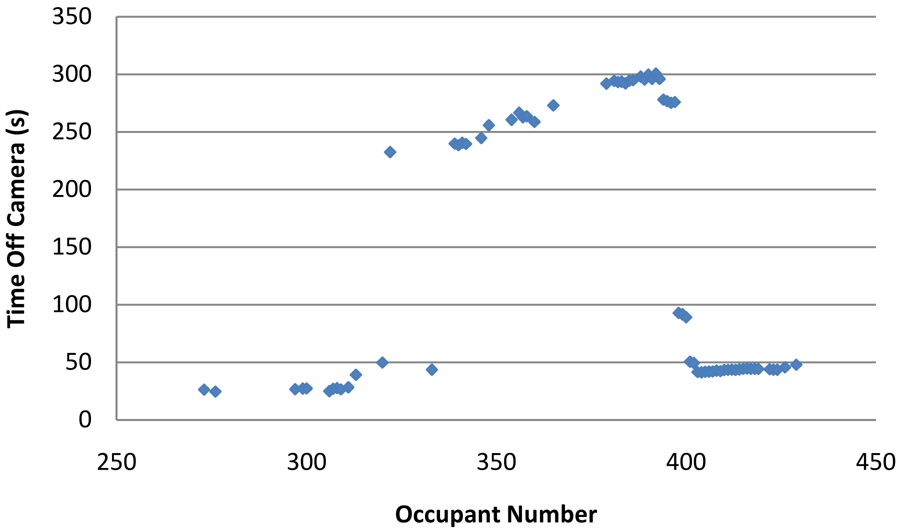

Figure 4-4: 5A, Floor 9 to 7 Time Off Camera vs. Occupant

4.7 Platoon Definitions and Assumptions

The hypothesis is that platoons of people descend the stairs differently based on interactions with others around them. The main assumption of the platoon analysis is that different platoons display different patterns in flow (therefore, different patterns in descent times). Platoon identification methods are summarized in the following list:

1. The platoon is spatially separated from the platoon ahead.
2. Platoons involving passing behavior(s) are separated from platoons that do not exhibit passing behavior(s).
3. Platoons with no passing, but display different descent time patterns (elongation, compression, equilibrium) are separated.
4. One-person platoons are separated.

A platoon is defined as a group of individuals who are spatially close from one person to the next and descend in the same approximate flow pattern. The measurement of how close a person is to another person in the stairwell was determined from the exit time gaps between individuals. The smaller the exit time gap, the closer the individual is to the person ahead.

In order to identify platoons, the data in the spreadsheets are manipulated to calculate time gaps from one occupant to the next, and to identify passing behavior. As stated in Section 3.2, occupants are assigned a number in the spreadsheet based on the order they exit the entire stairwell. The occupants within the spreadsheets are reordered for each floor that had a camera from first to exit to last to exit, and from first to enter to last to enter.

After the occupants are ordered from first to last on each floor with a camera, the exit time difference from one occupant to the next (exit time gap) and the enter time difference from one occupant to the next (enter time gap) are calculated. This is done by subtracting the exit/enter time of the occupant ahead from the exit/enter time of the occupant behind. For example, if the third occupant exits floor 4 at 60 s and the fourth occupant exits floor 4 at 63.5 s, the exit time gap for the fourth occupant is 3.5 s.

This analysis of platoons is limited to sections in the stairwell that contain no queues. At sections where queuing occurred, the assumption is that adjacent individuals passing the exit point are close to one another, regardless of their enter or exit time gap for that camera. Therefore, the large time gaps at sections affected by queues do not necessarily indicate a spatial separation between occupants, but are assumed to be due solely to the flow stoppage.

Average enter and exit time gaps with standard deviations from one person to the next are shown in Table 4-2. Again, averages are taken from data where queuing is determined to have not occurred. Also, data that is not affected by queues, but contains gaps greater than or equal to 10 s are omitted. This type of data makes up approximately 3.1% of the total data in Building 4 and approximately 2.0% of the data in Building 5, thus the gaps greater than 10 s are rare at sections of the stairwell with no queues. Because an estimation of the average separation that people travel within continuous flow during the majority of the evacuation is desired, this data is omitted from the averaging.

Since descent times are calculated in reference to exit times, exit time gaps are used to determine when a person is considered far away from another individual. An exit time gap greater than or equal to the average plus two standard deviations (for that stairwell) is the criterion used to classify a person as being in a separate platoon due to spatial separation.

Stair	Average Enter Time Gap in s (Standard Deviation)	Average Exit Time Gap in s (Standard Deviation)
4A	1.92 (1.06)	1.93 (0.99)
4B	1.84 (1.20)	1.79 (1.00)
5A	1.41 (0.81)	1.38 (0.75)
5B	1.53 (1.03)	1.58 (1.02)
All 4	1.89 (1.12)	1.87 (1.00)
All 5	1.46 (0.91)	1.47 (0.89)

Table 4-3: Average Enter and Exit Time Gaps with Standard Deviations

The frequency distributions of the data points for the exit time gaps presented in Table 4-3 are shown in Figure 4-5. The average exit time gap plus two standard deviations are 3.91, 3.79, 2.88, and 3.62 s for stairwells 4A, 4B, 5A, and 5B, respectively. Approximately 4.3%, 2.9%, 3.4%, and 2.8% of the exit gap data points not affected by queues are considered adequately separated from the person ahead for stairwells 4A, 4B, 5A, and 5B, respectively.

Occupants within flows involving passing behavior were shown to behave differently than occupants within flows not involving passing behavior by Hoskins [36]. Hoskins showed that certain occupants evacuating in a stairwell relatively close to one another within a continuous flow over one floor where no merging occurred had significantly different descent times that may be attributed to passing behavior and exit lane location [36].

Hoskins identified three different flow types within the overall flow over the one floor he analyzed. The flow types identified were (1) one where flow in both exit lanes (inner and outer)

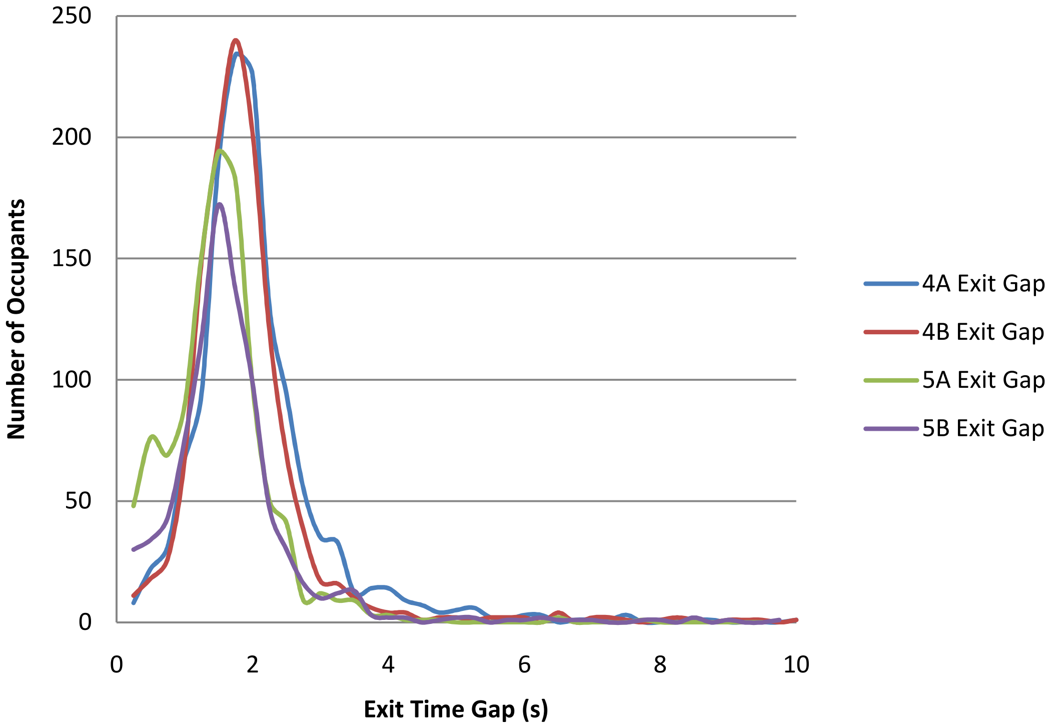

Figure 4-5: Exit Time Gap Frequency Distribution for Each Stairwell

moved in a unified manner where no passing occurred, with the exception of occupants who moved shoulder-to-shoulder, (2) one where occupants in the inner lane moved faster than the ones in the outer lane where passing occurred, and (3) one where occupants in the inner lane moved slower than those in the outer lane where passing occurred [36].

Thus, in addition to separating platoons based on spatial separation, platoons are separated into those where there is passing behavior exhibited by certain individuals distinguished from flows that contain no passing behavior. In the current study, passing behavior is identified as the passing of one (or multiple) occupant(s) by an occupant(s) from one camera exit to the next. Therefore, an occupant who exits after the person ahead on the upper floor in question, but exits before that same person on the lower floor is identified as a passer.[2]

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[2] Some passing events involve the same two occupants passing each other multiple times during the course of the descent. These occupants are identified as descending shoulder-to-shoulder, and are not considered actual passing events. Occupants who are found to pass each other at two or more consecutive cameras are considered shoulder-to-shoulder and are excluded from the analysis.

Three distinct patterns in the descent times between individuals in the same platoon are observed. These three patterns are identified as platoon (1) elongation, (2) compression, and (3) equilibrium. Platoon elongation occurs when the descent times increase (movement speeds decrease) from one occupant to the next, whereas platoon compression occurs when the descent times decrease (movement speeds increase) from one occupant to the next. Platoon equilibrium occurs when occupants descend at the same approximate speed.

It is possible to have a one-person platoon. Two scenarios occur for a one-person platoon: (1) A one-person platoon is an occupant who descends the entire length of the stair by themselves, and (2) A one-person platoon is an occupant who does not descend with a group who is either continually passed by other occupants, or passes other occupants during their entire descent.

Two sections of two different stairwells are observed for the platoon identification analysis. Within stairwell 4A, a flow of 177 occupants from the exit at the camera on floor 6 to the exit at the camera on floor 4 are observed. These occupants exit the landing at floor 6 between 168.91 and 489.23 s after the alarm sounded. During this time period, no occupants enter the stair on the 4th or 5th floors; thereby excluding any merging effects. In stairwell 5A, a flow of 181 individuals from the exit on floor 5 to the exit on floor 3 are observed. These occupants exit the landing at floor 5 between 280.01 and 545.91 s after the alarm sounded. Again, during this time, no occupants enter the stair on the 3rd or 4th floors.

Two-sample t-tests are used to compare the mean descent times between individuals within the same platoon and between adjacent platoons. These t-tests use the sample size and standard deviation to compare means from different samples. From the t-test, a p-value is calculated to determine whether the difference in the means of the two samples is random or signifies a difference in performance. The null hypothesis of all the comparisons is that the samples have the same average descent time. Therefore, the alternative hypothesis is that the two samples travel with different descent times. A 95% confidence interval is used to determine significance. Therefore, p-values less than or equal to 0.05 signify that the null hypothesis can be rejected and that the two samples have statistically different descent times. The null hypothesis fails to be rejected if the p-value between the two samples is greater than 0.05, thus inferring that the two samples have statistically similar descent times.

4.8 Merger Definition and Assumptions

A merger is defined as the situation when occupants from a floor join the flow of occupants on the stair. Both the enter and exit points are used as references when defining mergers. A limitation in the data set is that the enter points of those coming into the landing from the floor and those coming into the landing from the stair above are different. In buildings 4 and 5, the enter point of occupants coming into the landing from the floor is at the top of the outgoing stair, whereas the enter point of those coming into the landing from the incoming stair is the point where they are first seen entering the camera view (i.e. 2-4 steps leading to the main landing depending on the camera view). These differing enter points are shown in Figures 4-6 and 4-7 for buildings 4 and 5, respectively. In the analysis, a merger is assumed to have occurred when a floor occupant enters after a stair occupant, but exits directly in front of that same stair occupant.

This type of definition of merger is the most concrete way of defining the event with the data provided in the spreadsheets. In reality, the merge area occurs on the landing and differs in shape and size depending on different landing and stair geometries [32]. For data analysis, a point needs to be defined as the merge point (i.e. after such a point, the floor occupant is assumed to have merged with the stair flow). For the purpose of this study, this imaginary line is defined as the exit point of the occupants. Although the merge area occurs on the landing somewhere prior to the exit point, where the specific point actually occurs is unknown without reviewing the video footage.

Floor occupants can merge at two different positions within the stair flow. These individuals can either merge (1) directly in front of a person (or platoon) or (2) between people in a platoon. The scenario in which a person from the floor merges directly in front of a person descending the stair occurs when there are no other stair occupants ahead of the person who allows the merge.

People who come into the stair from a floor and exit after a stair platoon are not considered merging individuals. Merging persons are assumed to have an effect on the stair flow, therefore, those who exit after a person (or platoon) in the stair are assumed to have a negligible effect on the stair platoons. Only floor individuals who exit directly in front of stair individuals are assumed to have an effect on the flow and descent times of the people in the stair.

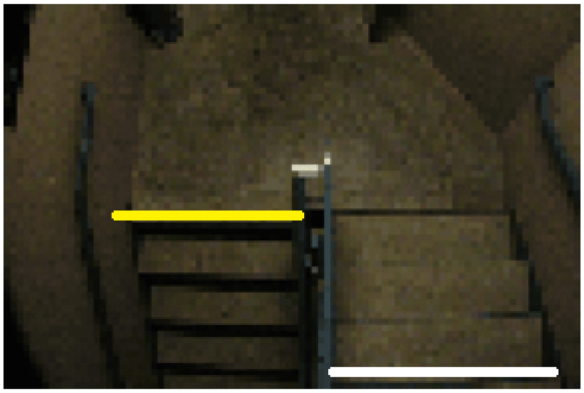

Figure 4-6: Building 4 Enter Points of Floor (Yellow) and Stair Occupants (White)

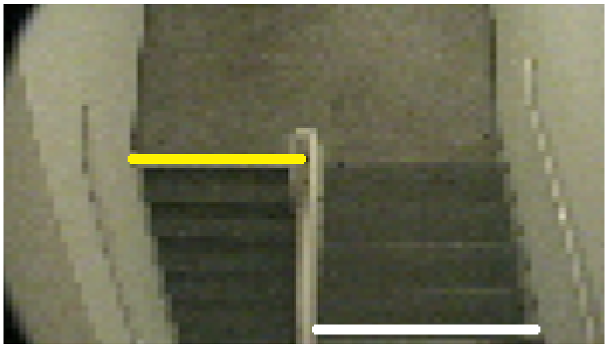

Figure 4-7: Building 5 Enter Points of Floor (Yellow) and Stair Occupants (White)

Depending on the floor that occupants enter the stair and the location of the video camera, mergers can either occur on or off camera. The definitions and assumptions stated above are used for occupants who merge on camera, however, these definitions and assumptions lose credibility during situations when people come into the stair off camera. Because there is a reliance on the enter and exit times in determining mergers, defining a merger off camera is difficult to do. To accurately handle off camera merger data, more assumptions must be made in addition to the on camera merger assumptions. Thus, in the current study, occupants who enter the stair off camera are not considered merging occupants. Instead, these occupants are considered a part of the stair flow, having descended a flight of stairs with the other stair occupants when first seen.

It must also be noted that merging analyses that utilize the enter and exit times of individuals will only be done in sections of the stairwells where no queues are determined to have occurred. Because queues can dramatically alter the enter and exit times from one occupant to the next, these values will not be used to determine merging effects.

Chapter 5: Results and Discussion

5.1 The Role of Density

As stated in Chapter 2, the method most commonly used in determining evacuation times is the hydraulic model. The hydraulic model assumes occupants behave homogeneously, and flow in the same manner with similar local speeds. These movement speeds are estimated using an equation (2) based on the density within the stair and the stair dimensions, i.e. the tread depth and riser height. From this speed, a specific flow can be calculated by multiplying the speed by the density. Then, using this specific flow and the effective width of the stairs, the calculated flow is determined by equation (5). Hence, using this approach, density is an important contributing factor to the determination of movement speeds on stairwells and other egress components.

The SFPE Handbook [3] does not, however, provide a specific way in which the density within the stair should be determined. It defines density as the level of crowdedness in the evacuation route measured in persons per unit area, but exactly what area and which individuals to count are debatable. The previous chapter provides an explanation of the two different approaches used to calculate density in the stairwells of buildings 4 and 5. One involves counting the number of people in camera view when an occupant enters the view. This assumes that the level of crowdedness in front of the occupant is the only factor in determining movement speed. The other method involves using the average number of people in camera view when an occupant enters and exits the camera view. This approach examines the level of crowdedness surrounding an individual rather than just in front.

After calculating local densities and local movement speeds for each occupant, each speed is paired with the density of the lower floor. Therefore, looking at a person’s local speed from the camera exit on floor 2 to the camera exit on floor 1, the density of the first floor is paired with this local speed. This assumes that the greatest factor in the determination of the speed from one camera to the next is the level of crowdedness of the landing downstream. Speed vs. density graphs of all of the data from the stairwells in buildings 4 and 5 are plotted with a linear trendline to compare the differing methods used, and to compare the data against the SFPE curve. The data are a complete range of densities varying from individuals in isolation to queues. These graphs are located in Appendix C and the R^2 values of each stairwell, as well as the R^2 values of data from both stairwells combined are given in Table 5-1 below.

Stairwell	Enter Density	Average Density
4A	0.25	0.29
4B	0.38	0.45
4A & 4B	0.28	0.33
5A	0.13	0.14
5B	0.10	0.10
5A & 5B	0.10	0.10

Table 5-1: Speed vs. Density R^2 Values

The R^2 values from Building 4 stairwells range from 0.25 to 0.45. In both stairwells, the enter density method results in lower R^2 values compared with the average density method. Combining all the data from Building 4, the R^2 values are 0.28 and 0.33 for the enter density and average density method, respectively. The R^2 values for Building 4 indicate that approximately 28% of the variation in movement speeds are explained by the enter density on the lower floor, and that approximately 33% of the variation are explained by the average density on the lower floor.

From the speed vs. average density plot of the Building 4 stairwells in Appendix C, the slope of the linear trendline of the stairwell data is -0.27, which is almost parallel to the SFPE Handbook line which has a slope of -0.29. However, the slope of the line generated from the enter density method is -0.23 and not parallel to the curve predicted by the SFPE Handbook. Also, the SFPE curve generally predicts greater speeds at the same densities as the data from the stairwells in Building 4. The SFPE equation allows for densities bounded by 3.75 persons/m^2, at which point the crowd is assumed to be so dense that movement is no longer possible. The highest densities calculated from the enter and average density methods in building 4 are approximately 2.65 and 2.12 persons/m^2, respectively. The landing and stair areas from the camera view used to calculate the density may account for these differences in the maximum density. It is noted, however, that for more dense situations (i.e. $D_{enter} \geq 1.57$ persons/m^2 and $D_{average} \geq 1.18$ persons/m^2) the SFPE curve predicts greater speeds than are actually observed.

Table 5-1 also provides values for the building 5 stairwell data. Stairwell 5A and 5B's R^2 values ranged from 0.10 to 0.14. Both density methods resulted in approximately the same R^2 values for the individual stairwells, as well as with the combined data set. The combined data set from both stairwell 5A and 5B resulted in an R^2 value of 0.10 using both density methods. It is apparent that density is not as accurate of a predictor of movement speed as it is for building 4. Only about 10% of the movement speeds in building 5 can be explained by the local density of the lower floor.

When comparing the Building 5 results to the SFPE curve, most of the speeds in the data are well below the SFPE curve predictions for the same densities. Also, as with Building 4, the maximum densities are less than the 3.75 persons/m^2 value. The maximum enter and average densities for the Building 5 stairwells are both 1.78 persons/m^2. These densities are smaller than the Building 4 maximum densities because the landing areas in the Building 5 stairwells are larger than the landing areas in the Building 4 stairwells. Also, the slopes of the linear trendlines of the Building 5 data are -0.21 and -0.20 for the average and enter density methods, respectively, thus showing a greater disparity between these slopes and the slope of the SFPE curve than is seen with the Building 4 data.

While density appears to play an important role in the determination of movement speeds down stairs, it is not the only factor that should be considered when assessing egress safety as demonstrated by the low R^2 values. Thus, there must be other factors contributing to the variation in the local speeds. One hypothesis is that platoon interactions are a probable factor in determining the speed at which occupants can move. A platoon analysis will be conducted in sections of the stairwells where no merging occurs to show how different platoons move within the overall flow. Also, passing and merging scenarios are examined to investigate how these phenomena affect descent times and outflows of individuals.

5.2 Platoon Analysis with No Merging

An analysis of how platoons travel within the overall flow is conducted for sections in the stairwell where no merging (on or off camera) occurs to gain an understanding of how platoons operate without other influencing factors. Platoons are identified using the methodology described in Section 4.7. The hypothesis is that different platoons in close proximity (i.e. within the average exit time gap plus two standard deviations) within continuous flow travel faster, slower, or at similar speeds from one platoon to the next. Continuous flow is defined as there being at least one occupant on the lower and upper landing, with the exception of the last person descending the stair.

5.2.1 Stairwell 4A

In stairwell 4A, no passing behavior was observed during the descent of the 177 occupants from the 6th to the 4th floors, with the exception of those occupants who descended the stair shoulder-to-shoulder. Platoons are identified based on the exit time gaps between individuals, and sub-platoons are identified based on descent time patterns.

Figure 5-1 shows the descent times of the occupants within this section of 4A vs. the number of occupants on the 4th floor landing when they entered the camera view. The associated R^2 value for the data points associated with this subpopulation is 0.25, which is consistent with the R^2 of all the data points in 4A shown in Section 5.1.

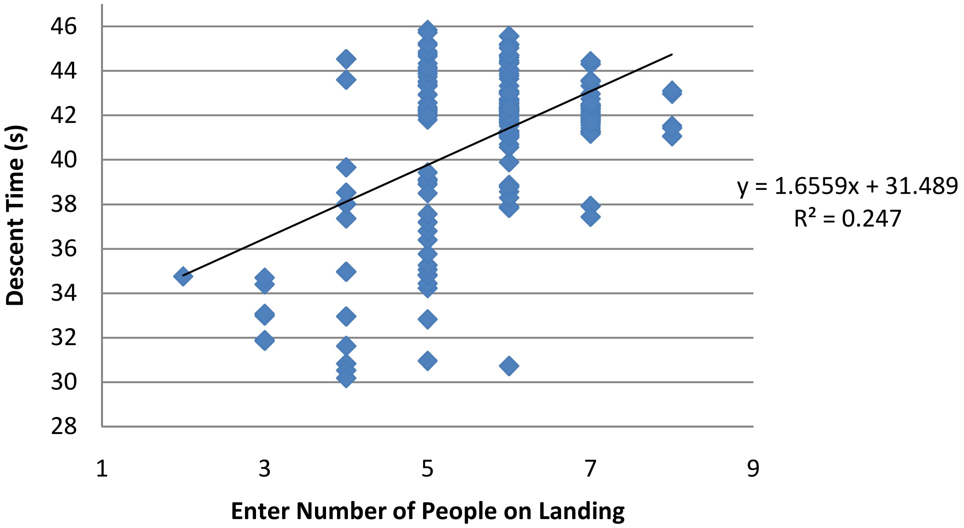

Figure 5-1: 4A Descent Time vs. Enter Number of Occupants on the 4th Floor

The results of the platoon analysis of the occupants descending in stair 4A from the 6th to the 4th floor when no merging occurs are shown in Table 5-2, and graphically represented in Figure 5-2. Table 5-2 shows the platoons with their average descent times and standard deviations. A total of 5 platoons are identified in this section of stair 4A based on exit time gap. Each of these platoons is then subdivided into sub-platoons based on descent time pattern. A plot of the descent times of all 5 platoons is provided in Appendix D.

Platoon	Number of Occupants Inner, Middle, Outer	Average Descent Time (s) with Standard Deviation
1	2,1,9	31.70 (1.06)
2	0,3,13	35.53 (1.15)
3	12,3,65	41.75 (2.01)
4	6,6,41	42.29 (0.68)
5	3,2,11	44.84 (0.63)

Table 5-2: 4A Platoon Average Descent Times with Standard Deviations

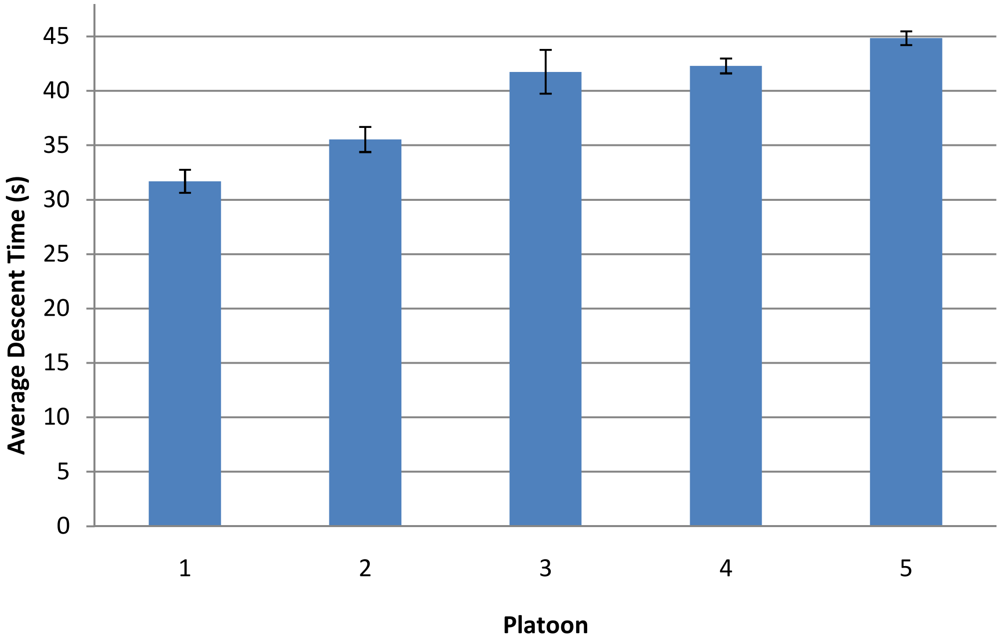

Figure 5-2: 4A Platoon Average Descent Times (error bars indicate S.D.)

Platoon 1 is made up of 12 occupants with two in the inner, one in the middle, and nine in the outer lanes. The average descent time and standard deviation of all the occupants in platoon 1 are shown in Table 5-2, and are 31.70 s (1.06). The 12 occupants in this platoon are then subdivided into sub-platoons A and B based on the differing descent time patterns observed. 1A consists of the first four members of platoon 1 who travel in platoon equilibrium. Although each member in 1A travels with a greater descent time than the person directly ahead, this change is determined to be insignificant (the greatest increase in descent time from one person to the next is 0.13 s). The last eight occupants in platoon 1 comprise sub-platoon B. As a whole, 1B travels in compression, with the last occupant having a lower descent time than the first occupant. The descent times decrease then increase by approximately 1 s every other to every two occupants with descent times gradually decreasing within the sub-platoon as a whole (see Fig.5-3).

In platoon 1, the occupants in the inner lane have an average descent time of 31.17 s (S.D. 0.64) and those in the outer lane have an average descent time of 31.98 s (1.02). The occupant in the middle lane is the tenth occupant in the platoon, and travels the fastest in platoon 1 with a descent time of 30.18 s. A t-test for the inner and outer lanes in platoon 1 gives a p-value of 0.27, so the null hypothesis that those in the inner and outer lanes have the same average descent time fails to be rejected.

T-tests are then used to compare the averages of the sub-platoons. 1A and 1B have average descent times of 32.96 s (0.1) and 31.07 s (0.64), respectively. A t-test between 1A and 1B results in a p-value of 5.0E-5. Thus, the null hypothesis is rejected, meaning the sub-platoons are traveling at statistically different speeds. 1B travels at a lower average descent time than 1A.

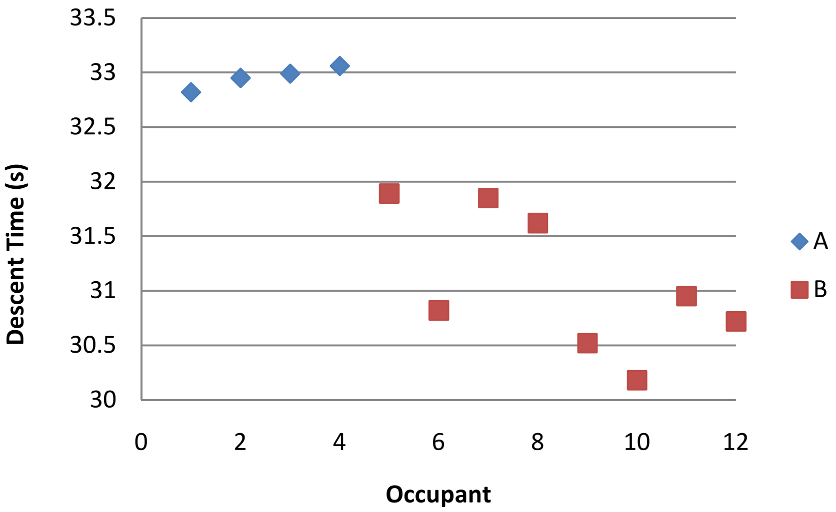

Figure 5-3: Platoon 1 Descent Times with Sub-Platoons

The next 16 occupants are identified as the second platoon. The average descent time and standard deviation of all the occupants in platoon 2 are shown in Table 5-2, and are 35.53 s

(1.15). The first occupant in platoon 2 is spatially separated from the last person in the first platoon by an exit time gap of 6.77 s at floor 4.

This platoon travels in both platoon equilibrium and elongation. The first 10 occupants in platoon 2 are sub-platoon A and travel in platoon equilibrium with slight fluctuations in the descent times from one person to the next. Sub-platoon B makes up the last six occupants who travel in elongation with each occupant slower than the person ahead. Figure 5-4 shows the descent times of the sub-platoons in platoon 2.

The three occupants who travel in the middle lane in platoon 2 have an average descent time of 35.86 s (1.29), with the average time of the 13 occupants who travel in the outer lane being 35.45 s (1.16). The p-value between these two lanes is calculated as 0.65; therefore, the occupants in both lanes travel with the same average descent times.

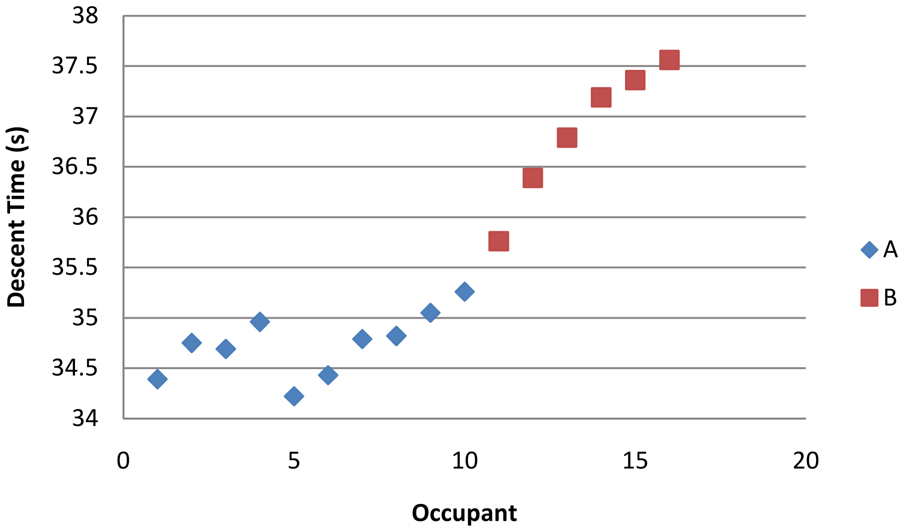

Figure 5-4: Platoon 2 Descent Times with Sub-Platoons

The equilibrium sub-platoon (A) has an average descent time of 34.74 s (0.32), whereas the elongation sub-platoon (B) has an average descent time of 36.84 s (0.68). A t-test comparing these two sub-platoons results in a p-value of 2.8E-4, meaning the two sub-platoons have significantly different descent times. The elongation sub-platoon at the end of platoon 2 travels significantly slower than the front portion of platoon 2, which travels in equilibrium.

Platoon 3 contains the largest amount of individuals in the analysis with the most sub-platoons, as well. The average descent time and standard deviation of all occupants in platoon 3 are shown in Table 5-2, and are 41.75 s (2.01). The first occupant in platoon 3 has an exit time gap of 3.94 s at the landing on floor 4. 80 occupants make up platoon 3 with 12 in the inner, 3 in the middle, and 65 occupants in the outer lanes. The average descent times are 42.44 s (1.91), 39.91 s (2.44), and 41.71 s (1.98) for the inner, middle, and outer lanes, respectively. A t-test between occupants in the inner and outer lanes results in a p-value of 0.24, so these lanes travel with the same average descent times. A t-test between the middle lane and the average of the rest of the platoon results in a p-value of 0.31. Thus, all the lanes in platoon 3 travel with the same average descent times.

The descent time patterns are more complex in platoon 3 compared to platoons 1 and 2. Nine distinct sub-platoons are identified and labeled A through I, with descent time patterns shown in Figure 5-5. From Figure 5-5, the majority of the time, the sub-platoons in platoon 3 alternate between equilibrium and elongation from one sub-platoon to the next.

As with platoons 1 and 2, platoon 3 begins with a sub-platoon traveling in equilibrium. The equilibrium in 3A is achieved through fluctuations between alternating elongating and compressing sections that may be attributed to lane switchers. The average descent time of 3A is 38.56 s (0.61), which is the lowest average descent time in platoon 3.

Following A is an elongating sub-platoon (B) which has an average descent time of 41.19 s (0.72). A t-test between 3A and 3B results in a p-value of 1.8E-7, indicating that the sub-platoons are traveling at significantly different descent times, with 3B moving slower than 3A.

Sub-platoon C contains nine individuals also traveling in elongation, but at a different elongation rate compared with 3B. It is interesting to note that the individuals in 3C all traveled in the outer lane from the 6th to the 4th floor; however, 3B has four individuals who switched from the middle to another lane or vice-versa during the descent. These lane switches may have caused 3B to have the fluctuations in descent times from one occupant to the next seen in Figure 5-5, due to differing lengths traveled in the two different lanes. The lane switches may be a cause of the different elongation rates between 3B and 3C, but more research is needed on this subject. The average descent time of 3C is 42.06 s (0.35). A t-test comparing 3C to 3B yields a p-value of 0.0069. So, the null hypothesis is rejected, and 3C travels slower on average than 3B, even though both travel in elongation.

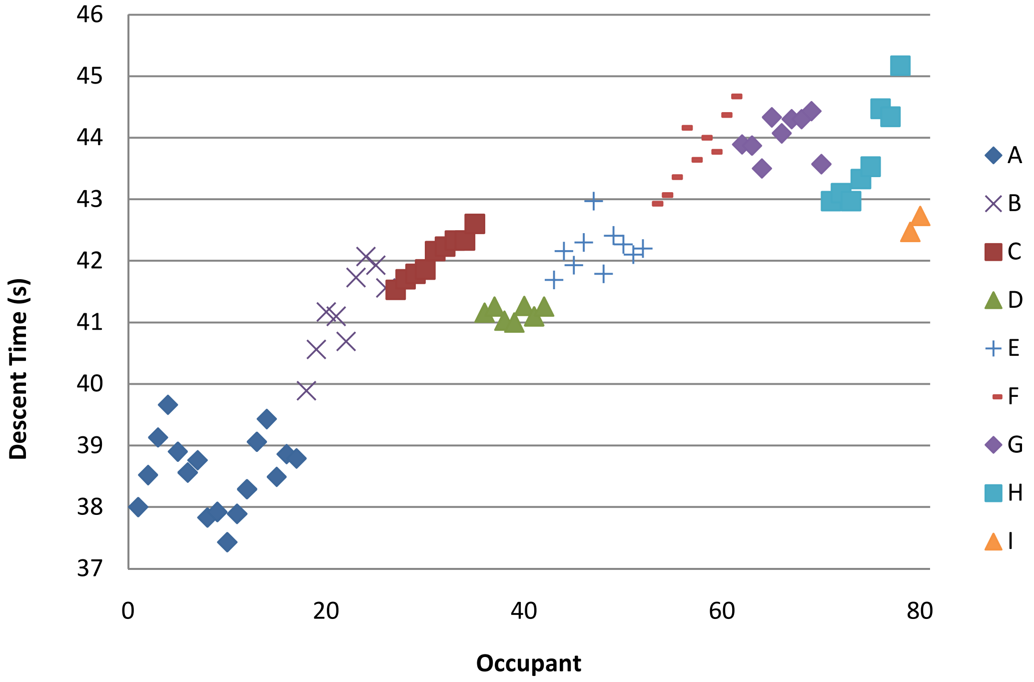

Figure 5-5: Platoon 3 Descent Times with Sub-Platoons

The next seven occupants are 3D. As Figure 5-5 shows, these individuals travel in platoon equilibrium with an average descent time of 41.15 s (0.11). A t-test between 3C and 3D produces a p-value of 2.8E-5. Thus, 3D travels faster on average than 3C. A t-test is then used to compare the average descent times of 3B and 3D. This t-test results in a p-value of 0.89, indicating that sub-platoons 3B and 3D travel statistically faster than 3C, and with the same approximate average descent times.

The next ten individuals make up sub-platoon E. Like 3D, 3E travels in equilibrium from the 6th to the 4th floor. The descent times of the occupants in E alternate between descent time increases and decreases fluctuating around the average. This fluctuation may again be attributed to lane switchers. In 3E, the fifth, sixth, and seventh occupants switched between the middle and another lane and vice-versa sometime during the descent from the 6th to the 4th floor. Again, more research is needed on the possible effects of lane switchers on descent time. 3E's average time to descend is 42.18 s (0.36). A t-test between 3D and 3E results in a p-value of 3E-6, so 3E travels significantly slower than 3D. A t-test is then performed to compare the average descent times of 3E and 3C. This produces a p-value of 0.46, indicating that both sub-platoons travel with the same approximate average descent time, which is significantly slower than the average of sub-platoons 3B and 3D.

Following 3E, sub-platoon 3F shows platoon elongation. The average descent time of 3F is 43.77 s (0.59). A t-test between 3F and 3E gives a p-value of 8.8E-6, so the two sub-platoons have significantly different descent times with 3F having the greater average.

The next nine occupants comprise sub-platoon 3G. These occupants travel in equilibrium with individual descent times fluctuating around the average of 44.03 s (0.34). Again, three occupants in 3G switch lanes during the descent, which may account for the descent time fluctuations. The first, third, and last occupants in 3G switch between the middle and outer lanes at one point during descent. A p-value of 0.28 results from a t-test comparison between 3F and 3G, indicating that the null hypothesis fails to be rejected. Thus, the two sub-platoons are assumed to travel with the same average descent times, even though 3F travels in platoon elongation and 3G travels in equilibrium.

Sub-platoon 3H follows 3G, and travels in elongation. 3H's average descent time and standard deviation are 43.74 s (0.82). From a t-test between 3H and 3G, a p-value of 0.37 indicates that the two sub-platoons travel with statistically similar average descent times, just as 3F and 3G travel with similar descent times.

Finally, sub-platoon 3I is the last in platoon 3. 3I contains two occupants who have a lower average descent time than all three sub-platoons preceding it (3F-3H). 3I's average descent time is 42.6 s (0.18). A t-test between 3H and 3I yields a p-value of 0.0076, indicating that 3I travels statistically faster than 3H. A t-test between 3E and 3I is performed to examine any similarity between the average descent times. A p-value of 0.096 indicates that these two have statistically similar average descent times. So, whatever causes sub-platoons 3F, 3G, and 3H to travel slower dissipates with 3I.

Platoon 4 consists of 53 occupants with 6 in the inner, 6 in the middle, and 41in the outer lanes. The average descent time and standard deviation of all the occupants in platoon 4 are shown in Table 5-2, and are 42.29 s (0.68). The occupants have average descent times and standard deviations of 42.19 (0.59), 42.62 (0.99), and 42.25 s (0.65) for the inner, middle, and outer lanes, respectively. A t-test between the inner and outer lanes gives a p-value of 0.83, so these two lanes travel with the same average descent times. A t-test comparing the occupants in the middle lane to the average of the rest of the group yields a p-value of 0.38. Therefore, occupants in all lanes travel with statistically similar descent times.

Four sub-platoons divide platoon 4 based on the different descent time patterns observed. These patterns are shown in Figure 5-6. The first occupant in platoon 4 has an exit time gap of

4.37 s at the landing on floor 4. This occupant has a descent time of 42.56 s, which is similar to the descent time average of sub-platoon 3I. So, based on descent time alone, this occupant could be placed in 3I; however, to stay consistent with the exit time gap identification of the groups, this occupant is included in platoon 4.

The majority of occupants in sub-platoon 4A travel in platoon compression, with the exception of the first occupant. The average descent time of 4A is 42.91 s (0.62).

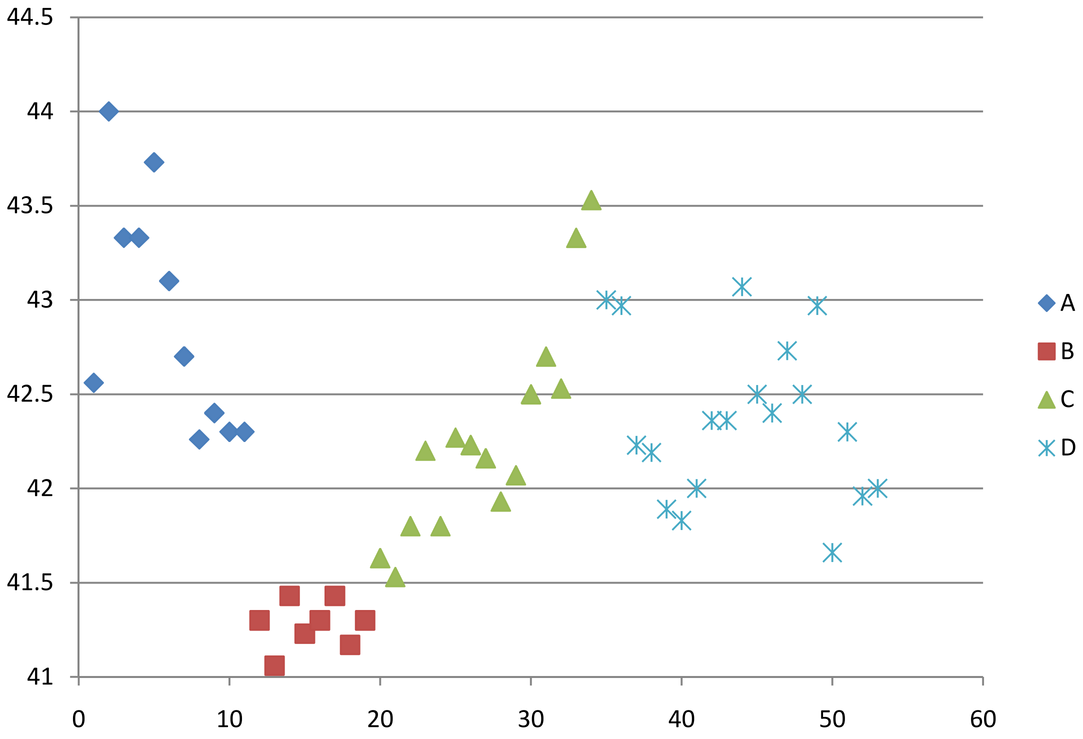

Figure 5-6: Platoon 4 Descent Times with Sub-Platoons

The next eight occupants are 4B. These occupants travel in platoon equilibrium with an average descent time of 41.28 s (0.12). A t-test between 4A and 4B produces a p-value of 3.4E-6, indicating that the two sub-platoons move with different average descent times. The equilibrium sub-platoon (4B) travels faster than the compression sub-platoon (4A).

Sub-platoon 4C consists of the next 15 occupants who move in platoon elongation. Their average descent time is 42.28 s (0.57). A t-test comparing 4B to 4C gives a p-value of 6.6E-6.

Therefore, the elongation of 4C travels on average statistically slower than the equilibrium of 4B. A t-test comparing the sub-platoons on both sides of the equilibrium sub-platoon is performed for 4A and 4C. This produces a p-value of 0.015, so the elongation sub-platoon (4C) following the equilibrium sub-platoon travels faster than the compression sub-platoon (4A) preceding the equilibrium sub-platoon.

4D is the last sub-platoon in platoon 4, and contains 19 individuals who travel in equilibrium with an average descent time of 42.36 s (0.43). Once again, the seemingly random fluctuations between some of the descent times of members in the sub-platoon may be associated with differing path lengths associated with lane switchers. In 4D, the third, seventh, tenth, fifteenth, and sixteenth occupants switch lanes at some point during the descent from the 6th to the 4th floor.

A t-test performed for 4C and 4D produces a p-value of 0.64, indicating that the two sub-platoons move with the same average descent times. Comparing the average of these two sub-platoons with the average descent time of 4A produces a p-value of 0.013, indicating that 4C and 4D combined travels statistically faster than 4A.

The last platoon observed in stairwell 4A is platoon 5. Platoon 5 contains 16 occupants with 3, 2, and 11 occupants in the inner, middle, and outer lanes, respectively. The average and standard deviation of the descent time for platoon 5 are shown in Table 5-2, and are 44.84 s (0.63). Occupants in the inner, middle, and outer lanes have average descent times of 45.23 s (0.49), 44.36 s (0.71), and 44.82 s (0.64), respectively. A t-test between the inner and outer lanes produces a p-value of 0.3, and a t-test between the middle lane and the average of the rest of the group yields a p-value of 0.46. Therefore, the individuals in differing lanes travel with the same average descent times.

Three sub-platoons divide platoon 5 based on differing descent time patterns, shown in Figure 5-7. The first occupant of platoon 5 has an exit time gap of 4.3 s at the 4th floor landing.

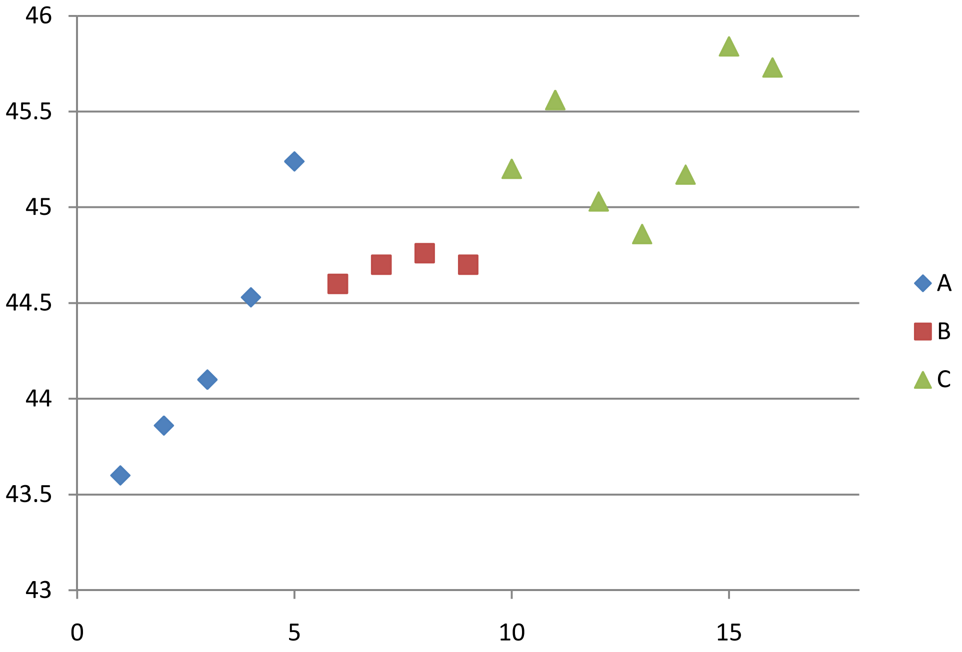

Figure 5-7: Platoon 5 Descent Times with Sub-Platoons

Sub-platoon 5A has five occupants traveling in platoon elongation. The average descent time of 5A is 44.27 s (0.64).

5B consists of the next four occupants who travel in platoon equilibrium. The average descent time of 5B is 44.69 s (0.066). A t-test between 5A and 5B results in a p-value of 0.22. Thus, the elongating sub-platoon (5A) and the equilibrium sub-platoon (5B) move with the same average descent times.

The last sub-platoon in 5 is 5C, and contains seven occupants. This sub-platoon contains fluctuations with increases and decreases in descent times as with 3B, 3E, 3G, and 4D, which may be attributed to lane switchers. The first, second, and fifth occupants in 5C switch between the middle and another lane sometime during the descent between the 6th and 4th floors. As a whole, 5C travels in platoon elongation. The average time to descend of 5C is 45.34 s (0.37). A t-test between 5B and 5C results in a p-value of 0.0031. Thus, the null hypothesis is rejected and the two sub-platoons have different average descent times with 5C traveling statistically slower than 5B, and, thus slower than 5A.

5.2.2 Stairwell 5A

Stairwell 5A contains some individuals who pass others from the 5th floor exit to the 3rd floor exit, unlike stairwell 4A, which has no passing over the two floors analyzed. As previously mentioned, Hoskins showed that platoons can be identified based on passing behavior [36]. Thus, platoons in this section of stairwell 5A are not only identified based on exit time gap and descent time patterns, but also on whether individuals within the platoon pass other individuals during the descent from the 5th to the 3rd floor. This results in identifying 13 platoons in 5A, with one being a one-person platoon who did not stay with a single platoon, but passes multiple individuals from the 5th to the 3rd floor.

Figure 5-8 shows the descent times of the occupants within this section of 5A vs. the number of occupants on the 3rd floor landing when they entered the camera view. As with the stair 4A platoon analysis, the associated R^2 value for the data points associated with this subpopulation is 0.14, which is consistent with the R^2 of all the data points in 5A shown in Section 5.1.

Results from the platoon analysis for stair 5A are shown in Table 5-3, and graphically in Figure 5-9. Table 5-3 shows the platoons with their average descent times and standard deviations. As mentioned, a total of 13 platoons are identified in this section of 5A based on exit time gap and passing behavior. A plot of the descent times of all 13 platoons is located in Appendix D.

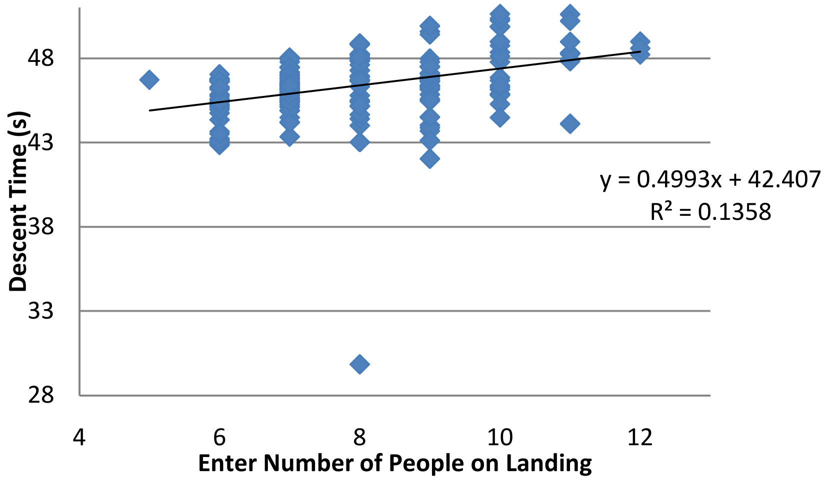

Figure 5-8: 5A Descent Time vs. Enter Number of Occupants on the 3rd Floor

The first platoon in the analysis consists of 11 occupants who have an average descent time and standard deviation of 45.57 s (1.34). Platoon 1 contains 3, 2, and 6 people in the inner, middle, and outer lanes, respectively. The average descent times of the inner, middle, and outer lanes are 44.46 (1.95), 46.25 (0.14), and 45.90 s (1.01). A t-test between the inner and outer lanes produces a p-value of 0.33, and a t-test between the middle lane and the average of the rest of the platoon produces a p-value of 0.13. Thus, the descent times of the lanes are not significantly different.

Platoon 1 contains passing behavior exhibited by three occupants. Two individuals pass one person during the descent, while another passes three people. The first person in the platoon travels in the outer lane and passes a person traveling in the inner lane, the fourth person travels in the inner lane and passes three individuals, two of whom switch between the outer and inner lanes and one who travels in the outer lane, and the ninth person travels in the inner lane and passes someone who descends in the outer lane. Thus, passing behavior is not common to just one lane.

An analysis of variation in descent times between those who pass others (passers), those passed (passed), and those who did not pass others nor are passed by others (others) is done for each platoon that contains passing behavior. Figure 5-10 shows the descent times of the passers, passed, and others for platoon 1.

Platoon	Number of Occupants Inner, Middle, Outer	Average Descent Time (s) with Standard Deviations
1	3,2,6	45.57 (1.34)
2	1,1,25	45.47 (1.14)
3	1,0,0	29.83 (-)
4	1,2,5	47.56 (1.28)
5	2,0,2	48.03 (0.24)
6	1,1,18	45.84 (0.85)
7	2,0,2	45.51 (0.07)
8	3,1,8	45.87 (1.46)
9	3,0,5	46.86 (0.61)
10	3,0,4	46.60 (1.44)
11	11,0,28	48.39 (1.20)
12	1,0,34	45.54 (1.41)
13	0,1,4	45.91 (0.37)

Table 5-3: 5A Platoon Average Descent Times with Standard Deviations

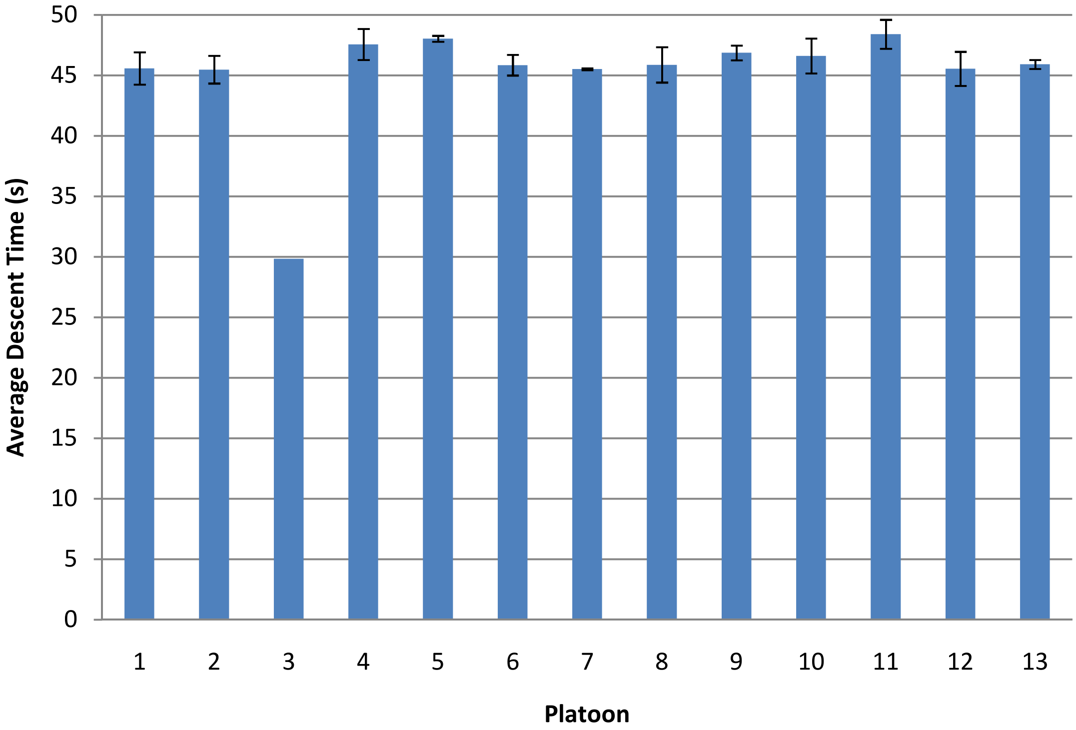

Figure 5-9: 5A Platoon Average Descent Times (error bars indicate S.D.)

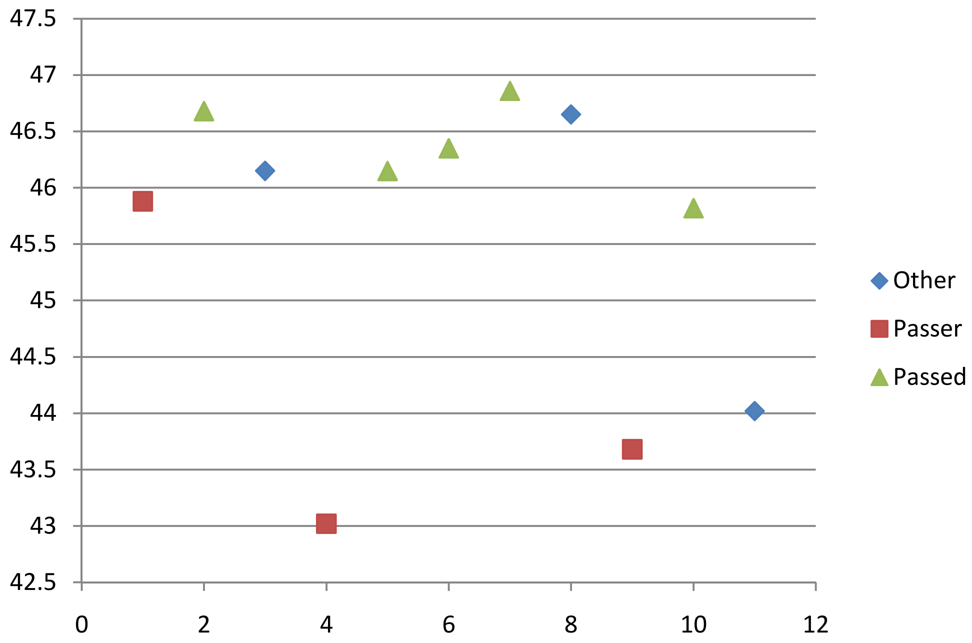

Figure 5-10: Platoon 1 Descent Times

The passers, passed, and others have average descent times of 44.19 (1.50), 46.37 (0.41), and 45.61 (1.40), respectively. A t-test between the passer and passed produces a p-value of 0.12, and a t-test between the others and the average of the rest of the platoon produces a p-value of 0.96. Thus, by just examining the passers, passed, and others, there are not significant differences in their descent times.

From Figure 5-10, the first passer in the outer lane and the individual who they passed in the inner lane do not have significantly different descent times; however, the other passers in the inner lane have relatively large differences in descent times with those who they passed. Therefore, a comparison of the average descent time of the inner lane passers, which is 43.35 s (0.47), is done to the average descent time of all others in the platoon, which is 46.06 s (0.85). A t-test between these two samples produces a p-value of 0.01, thus inferring that the inner lane passers require significantly less time to descend than all others in the group, including the outer lane passer.

Platoon 2 consists of 27 individuals with one person in the inner lane, one person in the middle lane, and 25 people in the outer lane. The descent time of the individual in the inner lane is 45.28 s, the descent time of the person in the middle lane is 46.72 s, and the average descent time of those in the outer lane is 45.48 s (1.16). Occupants in platoon 2 did not display any passing behavior, so the transition from platoon 1 to 2 stems from those in platoon 2 not feeling the need to pass, as is the case in platoon 1.

Platoon 2 is divided into two sub-platoons, A and B. 2A consists of the first five occupants who display platoon compression, and 2B consists of the next 22 occupants who display platoon elongation. The average descent time of 2A is 44.17 s (0.79) and the average descent time of 2B is 45.76 s (0.99). A t-test between 2A and 2B results in a p-value of 0.006, so the average descent times between the two sub-platoons are significantly different with 2B requiring more time to descend.

T-tests between the occupants in 2A and the platoon 1 inner lane passers, and between 2A and all others in platoon 1 are performed. A p-value of 0.17 results between 2A and the inner lane passers of platoon 1, while a p-value of 0.002 results between 2A and all others in platoon 1. Thus, 2A requires less time to descend than non-inner lane passers, but statistically requires the same amount of time to descend as the platoon 1 inner lane passers.

T-tests between 2B occupants and the platoon 1 inner lane passers and platoon 1 non-inner lane passers are also performed. A p-value of 0.026 results between 2B and the inner lane passers of platoon 1, while a p-value of 0.41 results between 2B and all others in platoon 1. Thus, 2B requires the same amount of time to descend as the non-inner lane passers, but requires more time to descend than the platoon 1 inner lane passers. Thus, the compression sub-platoon (2A) travels with the same average descent time as the platoon 1 inner lane passers, while the elongation sub-platoon (2B) travels with the same average descent time as the platoon 1 non-inner lane passers.

There is an occupant who exits the 3rd floor landing between occupants 18 and 19 of platoon 2 who is identified as a one-person platoon. During the descent from the 5th to the 3rd floor in stair 5A, this occupant does not stay with one platoon and passes a total of 13 people while in the inner lane. The descent time of this occupant is 29.83 s, significantly lower than all other platoons in the analysis. This one-person platoon is platoon 3.

The next platoon, platoon 4, is a passing platoon in which the first occupant, traveling in the inner lane, passes two occupants in the outer lane during the descent. Platoon 4 contains eight individuals.

Platoon 4 has an average descent time of 47.56 s (1.28). Platoon 4 consists of one person (the passer) in the inner, two people in the middle, and five people in the outer lanes. The descent time of the inner lane passer is 44.41 s, while the average descent times of the middle and outer lanes are 47.95 s (0.14) and 48.04 s (0.1) respectively. A t-test between the middle and outer lanes gives a p-value of 0.53. Thus, the middle and outer lanes in platoon 4 require the same amount of time to descend.

Again, an analysis of passers, passed, and others is done to compare descent times. The descent times of the passers, passed, and others in platoon 4 are shown in Figure 5-11. As with platoon 1, the passer in the inner lane has a significantly lower descent time than the rest of the platoon.

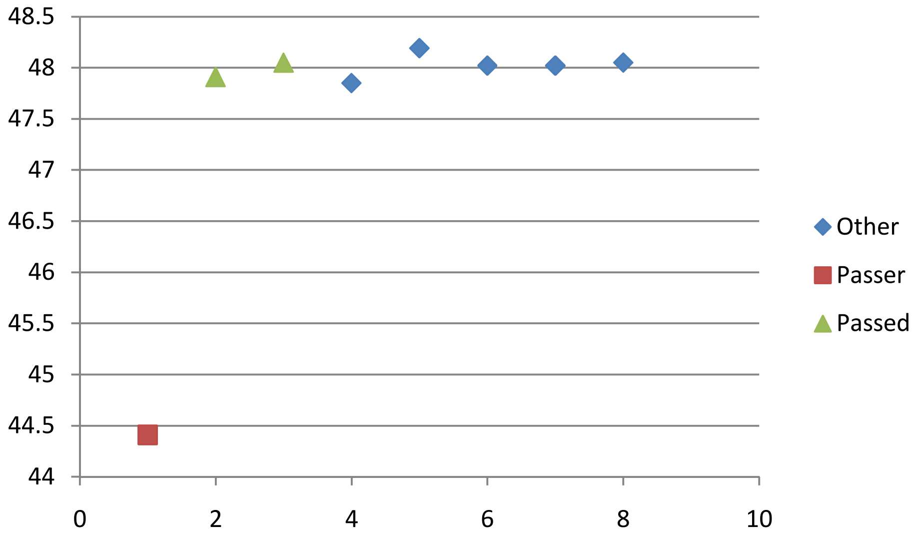

Figure 5-11: Platoon 4 Descent Times

The average descent times of those passed and others are 47.98 s (0.1) and 48.03 s (0.12) respectively. A t-test between those passed and others produces a p-value of 0.65. Thus, the passed occupants and the others in platoon 4 have statistically similar descent times. The average time to descend of those following the passer in platoon 4 (both those passed and others) is 48.01 s (0.11).

Platoon 5 consists of the next four occupants, and is distinguished from platoon 4 because the occupants in the inner lane in platoon 5 did not pass occupants. The average descent time of all occupants in platoon 5 is 48.03 s (0.24), and contains two occupants in the inner and two occupants in the outer lanes. Occupants in platoon 5 travel with the inner lane occupants (the first and last in the platoon) taking approximately 0.4 s longer to descend than outer lane occupants. The average descent time of the two inner lane occupants is 48.24 s (0.02) and the average descent time of the two outer lane occupants is 47.82 s (0.04). A t-test between the inner lane and outer lane occupants in platoon 5 results in a p-value of 0.018. Thus, occupants in the inner and outer lanes travel with different average descent times. T-tests are then performed between occupants in platoon 5 and occupants in platoon 4 following the passer. A t-test between inner lane occupants in platoon 5 and those following the passer in platoon 4 results in a p-value of 0.0015 and a t-test between outer lane platoon 5 occupants and those following the passer in platoon 4 results in a p-value of 0.012. Thus, the inner lane occupants in platoon 5 require more and the outer lane occupants require less time to descend than those following the passer in platoon 4.

The next 20 individuals are the sixth platoon. The average descent time of platoon 6 is 45.84 s (0.85). This platoon contains one instance of passing behavior with an occupant in the inner lane (first occupant in the platoon) passing an occupant in the outer lane. Platoon 6 has one occupant in the inner lane, one occupant in the middle lane, and 18 occupants in the outer lane. The descent times of the inner lane and middle lane occupants are 45.85 s and 44.88 s, and the average descent time of the outer lane occupants is 45.90 s (0.87). A plot of the descent times of platoon 6 is shown in Figure 5-12.

The descent time of the person who is passed in platoon 6 is 48.89 s, and the average descent time of the others in platoon 6 not directly involved with a passing event is 45.67 s (0.48). Performing t-tests between the others in platoon 6 and the inner and outer lanes of platoon 5 yield p-values of 2.4E-14 and 4.5E-13, respectively. Thus, the others (and the passer) in platoon 6 require significantly less time to descend than both the inner and outer lane occupants in platoon 5.

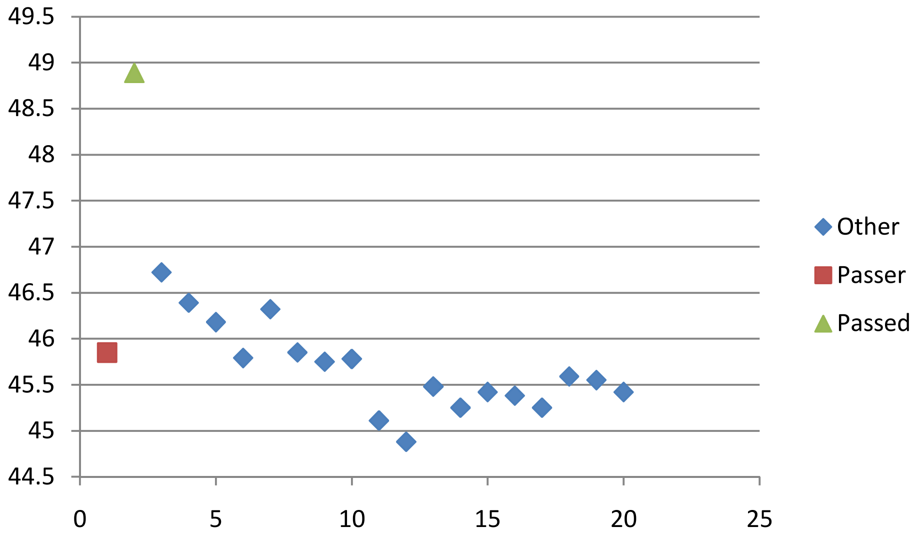

Figure 5-12: Platoon 6 Descent Times

Although both platoons 4 and 6 contain individuals who pass others, the patterns of the descent times of those following the initial pass are quite different. As Figure 5-12 shows, the others (blue diamonds) following the individual who is passed begin to compress with increasing speed (decreasing descent time) until equilibrium is reached at a lower descent time than the passer. This is different from what is seen with platoon 4 and the middle portion of platoon 1 where people following those passed travel in equilibrium with a descent time similar to that of the passed occupants (see Fig. 5-10, 5-11). The compressing followers of the sixth platoon, on the other hand, maintain descent times similar to the descent time of the passer. The differences in the descent time patterns could be due to the number of people passed. In the middle portion of platoon 1, one individual passes three people, and in platoon 4, the first individual passes two people, thereby possibly disrupting the descent of multiple individuals. This passing of multiple people may have more of an effect on the descent times of those following compared with the one individual passing seen in platoon 6.

The next four occupants make up the seventh platoon. The average descent time of platoon 7 is 45.51 s (0.07). Within platoon 7, no passing occurs. The first and third occupants travel in the inner lane and the second and fourth occupant travel in the outer lane. Platoon 7 travels in equilibrium. The average descent times of the inner and outer lanes are 45.56 s (0.05) and 45.47 s (0.06), respectively. A t-test comparing the inner and outer lanes produces a p-value of 0.26, thus the two lanes travel with the same average descent time.

A t-test between all the members of platoon 7 and the others in platoon 6 yields a p-value of 0.19. Thus, the platoon 7 occupants traveling in equilibrium descend with the same average time as the others in platoon 6.

The next 12 occupants make up platoon 8. The average descent time of the eighth platoon is 45.87 s (1.46). Platoon 8 has three instances of passing behavior. All passing events are occupants in the inner lane passing people in the outer lane. One passing event involves a person (occupant 6 in Fig. 5-13) passing two people, while the other two (occ. 1, 3) involve one-person passing.

Platoon 8 has three individuals in the inner, one individual in the middle, and eight individuals in the outer lanes. The descent time of the occupant in the middle lane is 46.79 s, and the averages of the inner and outer lanes are 43.73 s (1.47) and 46.56 s (0.33). A t-test between occupants in the inner and outer lanes produces a p-value of 0.077, so the occupants in these lanes travel with the same average descent time. As with platoons 1, 4, and 6, an analysis of variation in the descent times of the passers, those passed, and the others in the platoon who neither pass nor are passed is done. Figure 5-13 provides the descent times of the members in platoon 8.

Since all passers travel in the inner lane, their average descent time is given in the previous paragraph and is 43.73 s (1.47). Those passed by another occupant have an average descent time of 46.58 s (0.40). The other people in platoon 8 who neither pass anyone nor are passed by anyone have an average descent time of 46.58 s (0.28).

A t-test comparing those passed to others results in a p-value of 0.12, thus these two samples travel with the same average descent time. A t-test is then performed for passers vs. non-passers in platoon 8, resulting in a p-value of 0.076. This p-value indicates that the passers and non-passers in platoon 8 travel with the same average descent time, but this higher p-value is most likely due to the large variance in the single-person and two-person passers' descent times. The single-person passers have an average descent time of 44.58 s (0.10) and the two-person passer has a descent time of 42.04 s. A t-test between the single-person passers and the non-passers in platoon 8 results in a p-value of 2.0E-6, indicating that the single-person passers (thus, the two-person passer) require less time to descend than the non-passing individuals.

T-tests are then performed between members of platoon 8 with the occupants in platoon 7. A p-value of 0.017 is calculated between the platoon 8 single-person passers and platoon 7, while a p-value of 3.0E-6 is calculated between the platoon 8 non-passers and platoon 7. Thus, platoon 8 passers require less time to descend than platoon 7, while platoon 8 non-passers require more time to descend than platoon 7.

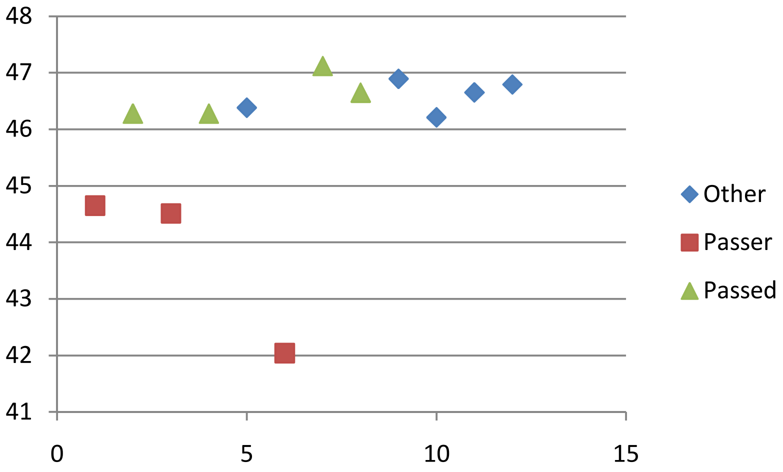

Figure 5-13: Platoon 8 Descent Times

As Figure 5-13 shows, all of the occupants marked as others in platoon 8 travel in equilibrium with approximately the same descent time as those passed. This is similar to the descent time patterns seen in platoon 4 (Fig. 5-11) and the middle portion of platoon 1 (Fig. 5-10). This type of behavior seems to be consistent when multiple people are passed by the same individual.

Platoon 9 contains eight individuals where no passing is observed. The average time to descend for the entire platoon is 46.86 s (0.61). This platoon has three people in the inner lane and five people in the outer lane descending in equilibrium. The average time to descend for the inner lane is 47.2 s (0.91) and the average descent time for occupants in the outer lane is 46.66 s (0.33). A t-test comparing the inner and outer lanes results in a p-value of 0.41, so the two lanes travel with the same average descent time.

All of the occupants in platoon 9 are then compared with occupants in platoon 8. A t-test comparing platoon 9 to the single-person passers in platoon 8 yields a p-value of 8.7E-6, and a t-test comparing platoon 9 to the non-passers of platoon 8 produces a p-value of 0.27. Thus, platoon 9 requires more time on average to descend than the passers of platoon 8, but requires the same average descent time as the non-passing members in platoon 8.

Platoon 10 has seven occupants with three in the inner and four in the outer lanes. The average descent time of platoon 10 is 46.6 s (1.44). Similar to platoon 1, platoon 10 contains passing individuals in both the inner and outer lanes. The first two occupants are in the outer lane and pass an inner lane occupant, while the fifth occupant is in the inner lane and passes an outer lane occupant.

The average descent time of the inner lane is 46.81 s (1.85) and the average descent time of the occupants in the outer lane is 46.44 s (1.34). A t-test comparing occupants in the inner lane to occupants in the outer lane produces a p-value of 0.79. Thus, both lanes travel with the same average descent time.

Figure 5-14 shows the descent times of platoon 10. The passers have an average descent time of 45.27 s (0.18), while those passed and the others have average descent times of 48.39 s (0.62) and 46.8 s (0.54), respectively. A t-test between those passed and others yields a p-value of 0.11, indicating that the two samples travel with the same average descent time. The average descent time of those passed and the others is 47.59 s (1.03). A t-test between platoon 10 passers and non-passers yields a p-value of 0.018, indicating that the passers require less time to descend than the rest of platoon 10.

T-tests between platoon 10 and 9 yield p-values of 1.0E-4 and 0.26 for platoon 10 passer to platoon 9 and platoon 10 non-passer to platoon 9, respectively. Thus, the non-passing members of platoon 10 require the same average descent time as platoon 9, while the passers require less time to descend than platoon 9.

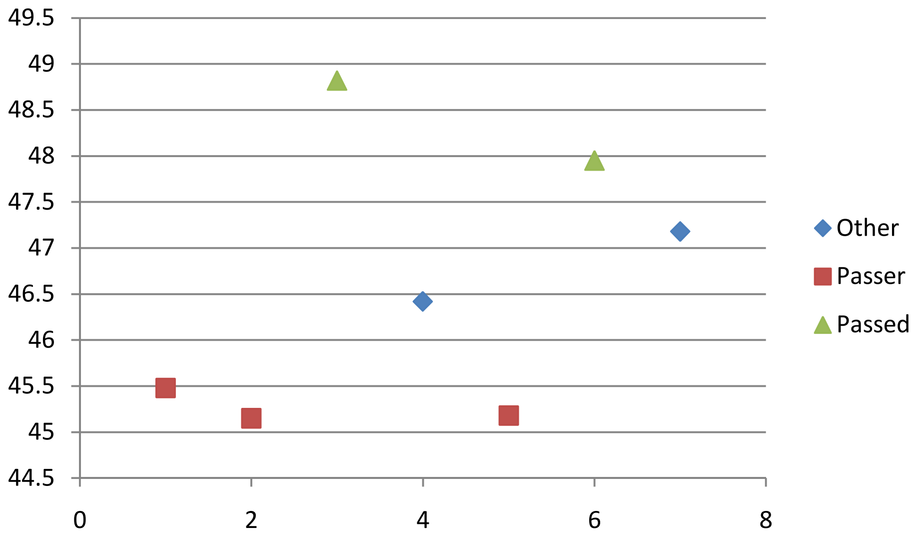

Figure 5-14: Platoon 10 Descent Times

The next 39 occupants are platoon 11. Within platoon 11, no passing occurs. There are 11 people who descend in the inner lane and 28 people who descend in the outer lane. The average descent times of the inner and outer lane occupants are 49.04 s (1.11) and 48.14 s (1.15), respectively. A t-test between occupants in the inner and outer lanes yields a p-value of 0.037, indicating that the inner lane occupants require more time to descend than the outer lane occupants.

T-tests comparing platoon 11 to platoon 10 are done, and yield p-values of 0.059 and 0.38 between platoon 11 inner lane occupants and non-passers in platoon 10 and platoon 11 outer lane occupants and non-passers in platoon 10, respectively. Therefore, although the two lanes move at different descent times in platoon 11, the two lanes both move at similar descent times to the non-passing individuals in platoon 10.

Platoon 11 is then divided into sub-platoons A and B based on differing descent time patterns. The first 29 members of platoon 11 consist 11A and travel in platoon elongation, while the last 10 occupants consist 11B and travel in platoon compression. Figure 5-15 shows platoon 11 descent times.

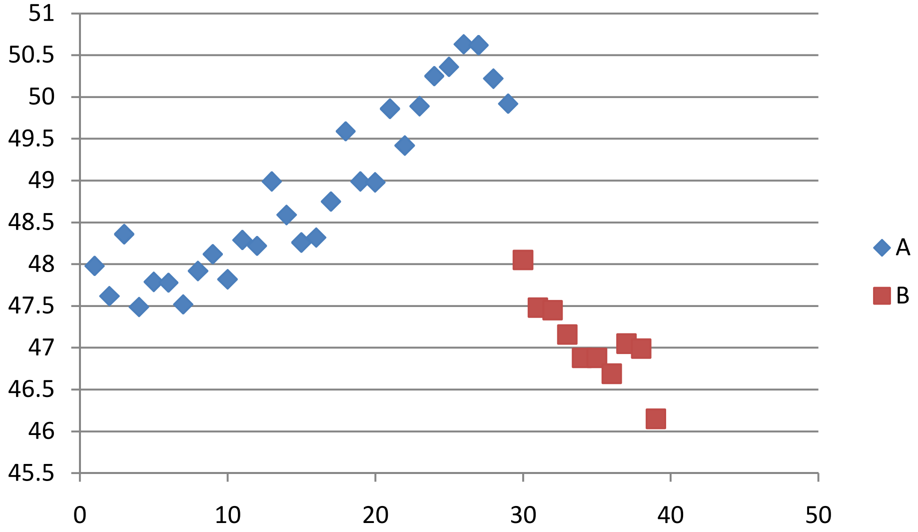

Figure 5-15: Platoon 11 Descent Times with Sub-Platoons

The average time to descend of 11A is 48.85 s (1.02), while the average descent time of 11B is 47.08 s (0.51). A t-test between 11A and 11B yields a p-value of 4.9E-8, inferring that the 11A requires more time to descend than 11B. T-tests between 11A and 11B are also done with the non-passing occupants in platoon 10. P-values of 0.087 and 0.4 are calculated between 11A and 10 non-passers and between 11B and 10 non-passers, indicating that 11A and 11B travel with the same average descent time as the platoon 10 non-passers.

The next 35 occupants are platoon 12. While no passing occurs just as in platoon 11, the first occupant in platoon 12 has an exit time gap of 2.94 s at the 3rd floor landing, which is greater than the average plus two standard deviations for stair 5A (2.88 s). Thus, platoon 12 is considered to be adequately spaced from platoon 11.

Platoon 12 has an average descent time of 45.54 s (1.41) with one occupant in the inner lane and 34 occupants in the outer lane. The inner lane occupant has a descent time of 46.12 s, and the average descent time of the outer lane occupants is 45.52 s (1.43). The 35 occupants in platoon 12 are divided into five sub-platoons based on descent time pattern, as shown in Figure 5-16.

12A travels in platoon equilibrium with an average descent time of 46.73 s (0.13), and is the slowest moving sub-platoon in platoon 12.

12B also travels in equilibrium, but at a lower average descent time than 12A. The average descent time of 12B is 46.22 s (0.05). A t-test between 12A and 12B yields a p-value of 9.1E-8, thus 12B takes significantly less time to descend than 12A.

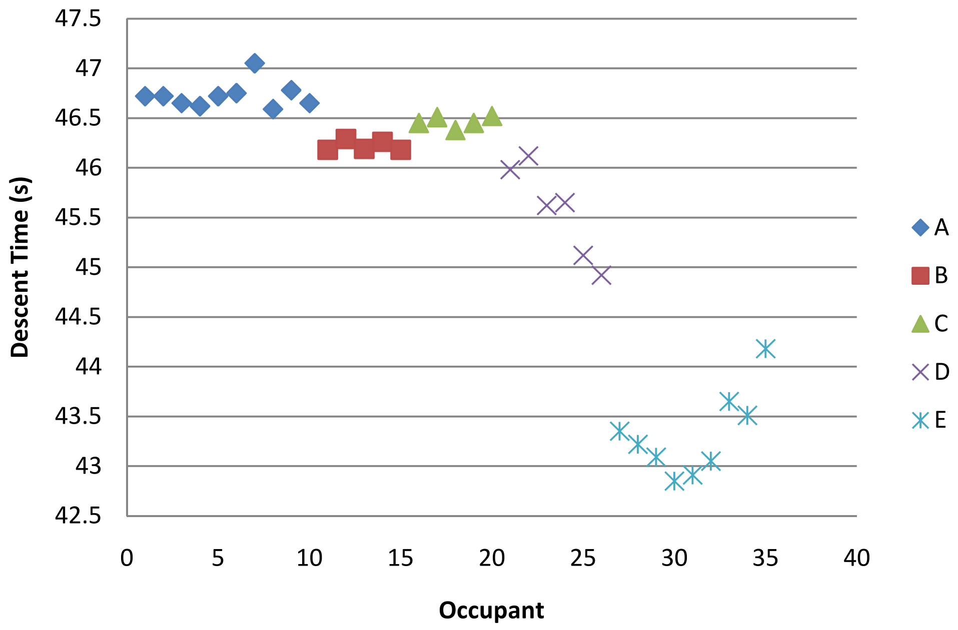

Figure 5-16: Platoon 12 Descent Times with Sub-Platoons

12C travels in equilibrium as well, but with a higher average descent time than 12B. The average descent time of 12C is 46.46 s (0.06). A t-test between 12B and 12C produces a p-value of 1.1E-4, inferring 12C takes statistically more time to descend. A t-test is then used to compare the equilibrium sections of 12A and 12C. This results in a p-value of 1.1E-4. Therefore, 12C travels in between the descent times of 12A and 12B; traveling statistically faster than 12A, but slower than 12B.

12D is the first sub-platoon in 12 to travel differently than equilibrium. 12D descends the stair in platoon compression with an average descent time of 45.57 s (0.47). A t-test comparing 12C to 12D results in a p-value of 5.3E-3, showing that 12D travels significantly faster than 12C.

The final sub-platoon, 12E, travels with the front portion in compression, and the rear in elongation. This is indicative of a sub-platoon where the faster occupants travel in the front and the slower occupants travel in the back of the platoon. The average descent time of 12E is the lowest in platoon 12 at 43.31 s (0.42). A t-test between 12D and 12E results in a p-value of

2.6E-6, thus 12E is moving significantly faster than 12D. As a whole, platoon 12 travels in platoon compression.

Platoon 13 is the final platoon in the stair 5A platoon analysis without merging. There is no passing behavior observed in platoon 13; however, 13 is separated from platoon 12 because the exit time gap on the 3rd floor of the first person in 13 is 2.94 s. Platoon 13 has an average descent time of 45.91 s (0.37) and consists of one occupant in the middle lane and four occupants in the outer lane. The middle lane occupant has a descent time of 46.15 s, and the average descent time of the four outer lane occupants is 45.85 s (0.40). Platoon 13 travels in platoon elongation with descent times increasing from occupant to occupant.

5.2.3 Discussion

The results of the platoon analyses with no merging show that there can be a range of descent times of individuals that descend close to one another within the stairwell. Three distinct platoon descent time patterns are observed within the high-rise stairwells: platoon 1) elongation, 2) compression, and 3) equilibrium. For the stair 4A platoon identification, there is no passing by the occupants, thus platoons are separated solely based on spatial separation. In stair 5A, however, passing is observed by individuals, thus platoons are separated based on both spatial separation and passing behavior. Some patterns in elongation/compression/equilibrium sequences and passing sequences are observed for the platoon identification in both stairwells.

The average descent times of the five platoons identified in 4A increase from the first platoon identified to the last (as seen in Figure 5-2). The largest increase in the average descent time occurs between platoons 2 and 3. Table 5-4 shows the descent time patterns of the five platoons identified in stair 4A.

Platoon	Descent Time Pattern
1	Equil - Comp
2	Equil - Elong
3	Equil - Elong - Equil - Elong - Equil - Elong - Equil
4	Comp - Equil - Elong - Equil
5	Elong - Equil - Elong

Table 5-4: Descent Time Patterns of Platoons in Stair 4A

As seen in Table 5-4, there is a descent time pulsation that alternates between platoon equilibrium and platoon elongation/compression. For each platoon in stair 4A, the average descent times of the lanes used by the occupants are statistically similar. However, for the majority (73%) of adjacent sub-platoons (separated by descent time patterns), the average descent times are statistically different.

Solely examining adjacent sub-platoons in stair 4A, six descent time pattern scenarios are observed. These six scenarios are:

1. Equilibrium followed by Compression
2. Compression followed by Equilibrium
3. Equilibrium followed by Elongation
4. Elongation followed by Equilibrium
5. Elongation (w/ lane switchers) followed by Elongation (w/out lane switchers)
6. Equilibrium (w/out lane switchers) followed by Equilibrium (w/ lane switchers)

For each of the preceding six scenarios, the following sub-platoon travels at a descent time that is either statistically slower/faster than the preceding sub-platoon, or is statistically similar to the preceding sub-platoon.

For scenario 1, the compression sub-platoon travels statistically faster than the preceding equilibrium sub-platoon. For scenario 2, however, the equilibrium sub-platoon travels statistically faster than the preceding compression sub-platoon. Since there are only two instances of compression sub-platoons found in stair 4A, this trend must be validated through future research to help determine whether this is a common trend for compression/equilibrium and equilibrium/compression patterns.

For scenario 3, the elongating sub-platoon travels statistically slower than the preceding equilibrium sub-platoon five times, while it travels at a statistically similar descent time once. For scenario 4, the equilibrium sub-platoon travels significantly faster than the preceding elongation sub-platoon twice, while it travels at a statistically similar descent time three times. From this small sample for scenario 3, the elongating sub-platoon typically travels slower than the preceding equilibrium sub-platoon. For scenario 4, the equilibrium sub-platoon typically travels similar to or faster than the preceding elongating sub-platoon. Again, more research is needed to validate the trends observed in the small sample.

Only one instance occurs for both scenarios 5 and 6. For scenario 5, the elongating sub-platoon with no lane switchers travels statistically slower than the preceding elongating sub-platoon with lane switchers. For scenario 6, the equilibrium sub-platoon with lane switchers travels statistically slower than the preceding equilibrium sub-platoon with no lane switchers. No definitive conclusions can be determined because of the small sample size of scenarios 5 and 6, thus future research is needed to validate the trends observed.

The average descent time values of the platoons in stair 5A contain more of an undulating pattern than the solely increasing average descent times of the platoons in stair 4A (see Figure 5-9). Platoons 1 through 11 in stair 5A contain an increasing/decreasing average descent time pattern that seems to be based on the passing/non-passing sub-platoons. Platoons 12 and 13 do not contain any passing events, but are separated from the other platoons based on spatial separation. Table 5-5 shows the descent time patterns and whether there is passing behavior observed in the 13 distinct platoons identified in stairwell 5A. Note that for the platoons that contain passing behavior (distinguished by a P in Table 5-5), the descent time pattern given is the pattern of the others (occupants not directly involved in the passing event).

Platoon	Descent Time Pattern	Passing Behavior
1	Equil	P
2	Comp - Elong	-
3	One Person	-
4	Equil	P
5	Equil	-
6	Comp - Equil	P
7	Equil	-
8	Equil	P
9	Equil	-
10	Equil	P
11	Elong - Comp	-
12	Equil - Comp - Elong	-
13	Elong	-

Table 5-5: Descent Time Pattern and Passing Behavior of Platoons in Stair 5A

As seen in Table 5-5, platoons 1 through 11 (with the exception of the one-person platoon) display an alternating pattern between passing platoons and non-passing platoons. Also, the majority of platoons 1 through 11 (64%), travel in equilibrium (not including the passers/those passed). Within stair 5A, the inner lane passers always travel significantly faster than the other occupants in the platoon, while this is not always the case for the outer lane passers.

Two of the platoons (1 and 10) involve passing that is not specific to just one lane, while the other passing platoons (4, 6, and 8) involve people in the inner lane passing people in the outer lane. The non-passing platoons 2 and 11 following the platoons where both the inner and outer lanes involve passers (platoons 1, 10), both contain an elongating portion that travels with an average descent time statistically similar to the non-inner lane passers of the preceding platoon and a compressing portion that travels with an average descent time statistically similar to the inner lane passers of the preceding platoon.

In platoons 1, 4, 6, and 8, the others following passing events either had average descent times similar to the passer or similar to those passed. The pattern seems to be dependent on whether just one or multiple occupants are passed. When multiple people are passed, the descent times of those following the passing event are similar to those passed, while when just one person is passed, the others following the event seem to take the passer’s descent time, or sometime in between the descent times of the passer and passed. This trend is further explored in section 5.3.

5.3 Passing Behavior and Effects

The stair 5A platoon analysis shows that passing individuals may have an impact on the local speeds of those whom they pass, and possibly people following those who are passed. In the analysis, occupants following individuals who are passed may take the passer’s speed, the speed of those who are passed, or a speed in between. The following section will provide the demographics of those directly involved with passing behavior to explore if any trends are present. Then, a descent time analysis for passing events is presented.

5.3.1 Passing Demographics

For both buildings examined, a list of those individuals directly involved with a passing event are observed and recorded. Those directly involved with a passing event are either a passer or a person who is passed from one camera exit to the next in the respective stairwells. Again, only those individuals who pass others or are passed by others from one camera exit to the next are considered, regardless of where the pass occurs. Therefore, a pass is considered the same type of event whether the pass occurs on camera or not. The data presented involves passes that occur during both continuous, free flowing conditions, and during queues. The demographics presented for each stairwell are gender and exit lane usage.

The demographics presented are separated between single-person passing events and multi-person passing events. Single-person passing events are: (1) an event where a passer passes one occupant from camera to camera, and (2) an event where a person is passed by one occupant from camera to camera. Multi-person passing events are: (1) an event where a passer passes more than one occupant from camera to camera, and (2) an event where a person is passed by more than one occupant from camera to camera.

5.3.1.1 Building 4 Stairs

The stairwells in Building 4 contain much less passing compared to those in Building 5. Overall a total of 43 passing events are observed in Building 4 with 21 events occurring in 4A and 22 events occurring in 4B.

The majority of the passes in both stairwells involve single-person passing, with this type of passing event occurring 71% of the time in 4A and 77% of the time in 4B. In 4A, during multi-person passing situations, the number of people passed ranges from two to seven people, while in 4B, the number of people passed ranges from two to three people.

Table 5-6 shows Building 4 single-person passer and passed separated by gender. The normalized percentages displayed in the table are with respect to the total numbers of males and females in the building. There are slightly more female single-person passers than there are male single-person passers, comprising 53% of the data. The genders of those passed by a single person are relatively split 51-49, male to female.

Table 5-7 shows Building 4 multi-person passer and passed separated by gender. Within Building 4 stairs, 63% of passers who passed multiple people are female, while 52% of those passed by multiple people are male. Thus, the numbers of male passed and female passed are relatively equal regardless of whether the pass is single-person or multi-person. However, females are found to be more likely to pass multiple people than males are in Building 4 stairs.

Gender	4A	4B	% of Total	Normalized %
Male Passer	7	9	50	47
Female Passer	8	8	50	53
Total	15	17		
Male Passed	10	9	54	51
Female Passed	7	9	46	49
Total	17	18		

Table 5-6: Building 4 Single-Person Passer and Passed by Gender

Gender	4A	4B	% of Total	Normalized %
Male Passer	3	1	40	37
Female Passer	2	4	60	63
Total	5	5		
Male Passed	4	2	55	52
Female Passed	4	1	45	48
Total	8	3		

Table 5-7: Building 4 Multi-Person Passer and Passed by Gender

The exit lanes where passers and passed descend are also reviewed to explore any trends with exit lane usage and passing behavior. Tables 5-8 and 5-9 show the results of these analyses for single-person and multi-person passing, respectively. The method of exit lane designation used in the analyses is given in Section 4.5.

Exit Lane	4A	4B	% of Total
Inner Passer	4	6	46
Middle Passer	5	3	36
Outer Passer	3	1	18
Total	12	10	
Inner Passed	4	1	18
Middle Passed	3	2	18
Outer Passed	6	12	64
Total	13	15	

Table 5-8: Building 4 Single-Person Passer and Passed by Exit Lane

Exit Lane	4A	4B	% of Total
Inner Passer	0	1	10
Middle Passer	0	3	30
Outer Passer	5	1	60
Total	5	5	
Inner Passed	1	0	11
Middle Passed	4	0	44
Outer Passed	1	3	44
Total	6	3	

Table 5-9: Building 4 Multi-Person Passer and Passed by Exit Lane

The majority of single-person passers in Building 4 stairs travel in the inner and middle lanes, comprising 82% of the observances. The majority of those passed by a single person travel in the outer lane, comprising 64% of the observances. For multi-person passing, virtually all passers travel in the outer and middle lanes, comprising 90% of the observances. The majority of those passed by multiple people travel in the outer and middle lanes, comprising 88% of the observances.

Next, an analysis of which gender passes which is done for stairs 4A and 4B. Tables 5-10 and 5-11 show the results of the single-person passing analyses.

Examining only single-person passers, 62% involve a male or female passing a male, while 38% involve a male or female passing a female. Male passing a single male and female passing a single male both occur 31% of the time, while male passing a single female and female passing a single female both occur 19% of the time.

Examining only those passed by a single person, female being passed by a single male is the least likely to occur at 15%. The event that occurs the most is male being passed by a single female at 30%, with male being passed by a single male and female being passed by a single female both at 27% of the total.

Gender	4A	4B	Total	% of Total
M pass M	5	5	10	31
M pass F	2	4	6	19
F pass M	5	5	10	31
F pass F	3	3	6	19

Table 5-10: Building 4 Single-Person Passer: Gender Scenarios

Gender	4A	4B	Total	% of Total
M passed by M	5	4	9	27
M passed by F	5	5	10	31
F passed by M	1	4	5	15
F passed by F	4	5	9	27

Table 5-11: Building 4 Those Passed by Single Person: Gender Scenarios

Tables 5-12 and 5-13 show the results of the multi-person passing analyses. Six scenarios are presented in the analysis of who passes who for multi-person passing. These include whether a male or female pass (or are passed by) a single-gender group or a mixed-gender group of people.

Approximately 55% of the people who pass multiple people pass a single-gender group, while about 44% pass a mixed-gender group. Approximately 63% of the people passed by multiple people are passed by a single-gender group, while about 36% are passed by a mixed-gender group.

Out of the multi-person passers, the events that occur the most are split between male passing all male, female passing all male, male passing mixed-gender, and female passing mixed-gender, which all occur approximately 22% of the time. The event that occurs the least is male passing all females, which does not occur at all in this sample.

The events that occur the most out of those passed by multiple people are split between female passed by all male and male passed by mixed-gender, which both occur about 36% of the time. The events that occur the least are split between male passed by all female and female passed by mixed-gender group, which do not occur at all. It is important to note that gender is just one factor in the data presented in Tables 5-12 and 5-13. Other factors may play a role in the results presented, such as social group formation and queuing. The tables presented in this section are available in graphical form in Appendix E.

Gender	4A	4B	Total	% of Total
M pass All M	1	1	2	23
M pass All F	0	0	0	0
F pass All M	1	1	2	22
F pass All F	0	1	1	11
M pass Mix	2	0	2	22
F pass Mix	1	1	2	22

Table 5-12: Building 4 Multi-Person Passers: Gender Sequences

Gender	4A	4B	Total	% of Total
M passed by All M	2	0	2	18
M passed by All F	0	0	0	0
F passed by All M	4	0	4	37
F passed by All F	0	1	1	9
M passed by Mix	2	2	4	36
F passed by Mix	0	0	0	0

Table 5-13: Building 4 Multi-Person Passed: Gender Sequences

5.3.1.2 Building 5 Stairs

The stairwells in Building 5 contain more passing situations compared to the Building 4 stairwells. Overall, Building 5 has a total of 231 passing events with 128 coming from stair 5A and 103 from stair 5B.

The majority of the passes in both stairwells involve single-person passing, with this type of passing event occurring 65% of the time in both 5A and 5B. In 5A, during multi-person passing situations, virtually all of the number of people passed ranges from two to six people, while in 5B, virtually all of the number of people passed ranges from two to seven people.[3]

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[3] One-person platoon data are not included in the passing demographic analyses. Two instances of a one-person platoon passing multiple people occur, one in 5A and one in 5B.

Table 5-14 shows Building 5 single-person passer and passed separated by gender. There are slightly more male single-person passers, comprising 54% of the total. There are more females passed by a single person than there are males passed by a single person, comprising 57% of the total.

Table 5-15 shows Building 5 multi-person passer and passed separated by gender. There are more females who pass multiple people than there are males who pass multiple people, comprising 56% of the data. There are slightly more males passed by multiple people than there are females passed by multiple people at 53% of the total data.

Gender	5A	5B	% of Total	Normalized %
Male Passer	41	42	59	54
Female Passer	33	24	41	46
Total	74	66		
Male Passed	40	34	49	43
Female Passed	46	31	51	57
Total	86	65		

Table 5-14: Building 5 Single-Person Passer and Passed by Gender

Gender	5A	5B	% of Total	Normalized %
Male Passer	20	20	49	44
Female Passer	25	16	51	56
Total	45	36		
Male Passed	21	24	58	53
Female Passed	20	12	42	47
Total	41	36		

Table 5-15: Building 5 Multi-Person Passer and Passed by Gender

The exit lanes where passers and passed descend are also reviewed to explore any trends with exit lane usage and passing behavior. Tables 5-16 and 5-17 show the results of these analyses for single-person and multi-person passing, respectively. The majority of passers (either single-person or multi-person passers) travel in the inner lane. 71% of single-person passers and 81% of multi-person passers travel in the inner lane. The majority of people passed (either by a single person, or by multiple people) travel in the outer lane. 85% of those passed by a single person and 91% of those passed by multiple people travel in the outer lane.

Exit Lane	5A	5B	% of Total
Inner Passer	56	42	71
Middle Passer	7	0	5
Outer Passer	14	19	24
Total	77	61	
Inner Passed	9	12	14
Middle Passed	1	1	1
Outer Passed	79	47	85
Total	89	60	

Table 5-16: Building 5 Single-Person Passer and Passed by Exit Lane

Exit Lane	5A	5B	% of Total
Inner Passer	36	26	81
Middle Passer	7	0	9
Outer Passer	1	7	10
Total	44	33	
Inner Passed	2	4	8
Middle Passed	0	1	1
Outer Passed	44	25	91
Total	46	30	

Table 5-17: Building 5 Multi-Person Passer and Passed by Exit Lane

As with Building 4 stairs, an analysis of which gender passes which is done for stairs 5A and 5B. Tables 5-18 and 5-19 show the results of the single-person passing analyses.

Examining only single-person passers, 36% involve a male passing another male, while 24% and 23% involve a male passing a female and female passing a male, respectively. The event that occurs the least out of the single-person passers involves a female passing another female at 17% of the total.

Examining only those passed by a single person, female being passed by a single male is the most likely to occur at 30%, followed by male being passed by a single male and male being passed by a single female at 25% and 24%, respectively. The least likely to occur is female being passed by a single female at 21%.

Gender	5A	5B	Total	% of Total
M pass M	19	30	49	36
M pass F	21	12	33	24
F pass M	18	14	32	23
F pass F	13	10	23	17

Table 5-18: Building 5 Single-Person Passer: Gender Scenarios

Gender	5A	5B	Total	% of Total
M passed by M	21	16	37	25
M passed by F	17	18	35	24
F passed by M	25	19	44	30
F passed by F	19	12	31	21

Table 5-19: Building 5 Those Passed by Single Person: Gender Scenarios

Tables 5-20 and 5-21 show the results of the multi-person passing analyses. As with the Building 4 stairs, six scenarios are presented in the analysis of who passes who for multi-person passing.

In Building 5 stairs, approximately 41% of the people who pass multiple people pass a single-gender group, while about 58% pass a mixed-gender group. Approximately 54% of the people passed by multiple people are passed by a single-gender group, while about 46% are passed by a mixed-gender group.

Out of the multi-person passers, the events that occur the most are split between female passing mixed-gender and male passing mixed-gender, which occur 32% and 26% of the time, respectively. The event that occurs the least is female passing all female, which occurs 6% of the time.

The event that occurs the most out of those passed by multiple people is female passed by mixed-gender, which occurs 25% of the time. Male passed by all male and male passed by mixed-gender are the events that are the next most likely to occur at 22% and 21%, respectively.

The event that occurs the least is female passed by all female, which occurs 7% of the time. Again, gender is just one factor in the data presented in Tables 5-20 and 5-21. As with Building 4 stairs, the tables presented in this section are available in graphical form in Appendix E.

Gender	5A	5B	Total	% of Total
M pass All M	2	7	9	13
M pass All F	4	4	8	12
F pass All M	4	3	7	10
F pass All F	2	2	4	6
M pass Mix	10	8	18	27
F pass Mix	11	11	22	32

Table 5-20: Building 5 Multi-Person Passers: Gender Sequences

Gender	5A	5B	Total	% of Total
M passed by All M	4	12	16	22
M passed by All F	7	4	11	15
F passed by All M	5	2	7	10
F passed by All F	1	4	5	7
M passed by Mix	8	7	15	21
F passed by Mix	12	6	18	25

Table 5-21: Building 5 Multi-Person Passed: Gender Sequences

5.3.1.3 Discussion

Before discussing the similar trends in gender and lane demographics of the passers/passed in the stairs in Buildings 4 and 5, it is important to note an interesting passing trend that occurs in the Building 5 stairwells related to the merging of occupants. Many occupants who merge into the stair flow on their floor of entry are passed by those who allow the merge by the time they reach the next camera view. Of the 128 observed passing events in 5A, 51 occupants pass an individual who merges in front of them by the next camera view exit. This type of passing behavior accounts for approximately 40% of the observed passing scenarios. Of the total 139 occupants passed in stair 5A, 52 are passed sometime between their entry floor and the next camera view exit by at least one individual who allows them to merge. Thus, approximately 37% of those observed to have been passed are passed between their entry floor and the next camera view exit. It is important to note that this number is likely to be higher with cameras at every floor because passing and merging situations are bound to have occurred off-camera, but are not reflected in the current analysis.

In stair 5B, of the 103 passing events observed, 40 occupants pass an individual who merges in front of them by the next camera view exit. This accounts for approximately 39% of the observed passing scenarios; similar to the 40% of passers found in stair 5A. Of the 102 occupants passed in stair 5B, 33 are passed sometime between their entry floor and the next camera view exit by at least one individual who allows them to merge. Thus, approximately 32% of those observed to have been passed are passed between their entry floor and the next camera view exit.

A comparison between the results of the passing demographic analyses in the stairwells of Building 4 and Building 5 is presented to determine any trends that are similar across the two buildings. Because the sample size is so small (only for two buildings), the similar trends presented must be verified through more research in other high-rise office building stairwells.

Within both the Building 4 and Building 5 stairwells, the majority of single-person passers travel in the inner lane, while the majority of those passed by a single person travel in the outer lane. Also, within both buildings’ stairwells, the single-person passing scenario that occurs most often is a single male passing male, and the single-person passing scenario that occurs least often is a single female passing female.

When examining multi-person passing, within both buildings’ stairwells there are more females who pass multiple people than males who pass multiple people. Also, within both buildings’ stairwells, there are slightly more males who are passed by multiple people than females who are passed by multiple people. Within both buildings, the majority of those passed by multiple people travel in the outer lane.

Although there are some similar trends between which lane is typically used by passers/passed, it is important to note that the majority of people descended in the outer lane, and that all stairwells in Buildings 4 and 5 are sinistral-descending stairs. In sinistral-descending stairs, the outer lane is on the right side of the stair, while the inner lane is on the left side of the stair (from the point of view of someone descending). Thus, it is important to note that the passing lane may have been the inner lane because it is on the left side of the stair. Because these two buildings are located in the US, there may be a tendency to stay to the right, opposed to other countries where it may be custom to stay to the left. Stairwells within buildings in other countries where people typically travel on the left and dextral-descending stairwells should be examined to determine whether the passing lane is based on the inner/outer lane of the stair or the right/left side of the stair.

5.3.2 Passing Behavior and Effects on Descent Times

While examining stairwells in Building 5, a trend in the descent times of those following passing events was discovered. The occupants classified as “others” in the analysis who follow a passing event either had descent times similar to the passer or similar to those passed. An analysis of specific observed passing events in all four stairwells of the two buildings is presented to explore the descent time trends of those following a passing event.

All the passing events presented in the following section occur over a section in the stairwell where no queues are present. Queues may affect descent times in an unpredictable manner; therefore, passing events over sections that experience queues are not analyzed.

Passing events involving individuals (passer, passed, or other) who also allow a merge on either floor observed are not presented in the following section. Individuals only experiencing a passing event are presented to avoid possible effects on descent times that merging may cause.

As with the passing demographic analysis, those occupants who descend the stairwell shoulder-to-shoulder are not included in the analysis.

5.3.2.1 Building 4 Stairs

Six instances of passing behavior involving occupants not affected by mergers and/or sections of queuing are observed in both stairwells 4A and 4B. Tables 5-22 and 5-23 summarize the passing events for stairs 4A and 4B, respectively.[4] The numbers of passers, those passed, and others are given for each passing event. If there is more than one passer/passed/other, the descent times of the passer/passed/others are given as the average with standard deviation in parentheses. Otherwise, the single passer/passed/other descent time is given.

For passing events involving only one passer and/or one passed, similarity is based on the average plus or minus two standard deviations. Thus, if a passer or someone passed has a descent time that lies within two S.D.'s of the average descent time of the others, then the two are assumed to be statistically similar. Those descent times that do not lie within two S.D.'s of the average descent time of the others are assumed to be statistically different.

Two sample t-tests are performed for those samples with more than one person to compare average descent times. P-values are calculated from these t-tests and are provided in the descent time tables below.

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[4] Appendix F contains the data presented in the tables in graphical form.

Pass Event	Description	# of Others	Passer Des. Time (s)	Passed Des. Time (s)	Other Des. Time (s)	p-value
1	1 pass 1	5	45.38	51.75	45.35 (1.26)	
2	1 pass 1	5	24.72	32.46	27.99 (0.86)	
3	1 pass 1	11	37.74	39.87	38.88 (0.35)	
4	1 pass 2	2	39.14	44.7 (0.59)	39.51 (0.33)	0.02
5	1 pass 1	4	41.57	44.31	41.94 (0.87)	
6	1 pass 1	3	42.97	45.17	44.08 (0.11)	

Table 5-22: Descent Times of Passing Events in Stair 4A

Pass Event	Description	# of Others	Passer Des. Time (s)	Passed Des. Time (s)	Other Des. Time (s)	p-value
1	4 pass 1	4	28.58 (1.24)	37.65	29.4 (0.41)	0.28
2	1 pass 1	11	97.76	100.8	98.17 (0.41)	
3	1 pass 1	4	45.51	48.55	45.88 (0.43)	
4	1 pass 1	6	58.56	60.23	57.5 (0.45)	
5	1 pass 1	12	65	67.17	65.25 (0.46)	
6	2 pass 1	6	61.78 (0.07)	66.14	61.65 (0.52)	0.58

Table 5-23: Descent Times of Passing Events in Stair 4B

As shown in Tables 5-22 and 5-23, the majority of the passing events occurring in the Building 4 stairwells involve single-person passing. Thus, p-values are only able to be calculated for three of the twelve passing events (event 4 in 4A, 1, 6 in 4B). Within stair 4A, five out of the six passing events examined involve single-person passing. The other event involves a person passing two people. Within stair 4B, four out of six passing events examined involve single-person passing. The other two events involve four people passing one person and two people passing one person.

Within stair 4A, the others travel with descent times similar to the passer's descent time in three of the six cases. These three cases are events 1, 4, and 5. In event 4, a t-test between the average descent times of those passed and the others results in a p-value of 0.02, inferring that the null hypothesis is rejected and that the two samples require different times to descend. In event 4, the passer’s descent time is within two S.D.’s of the average descent times of the others. In passing events 1 and 5, the passer’s descent times are within one S.D. of the average descent times of the others. However, the descent times of those passed are not within two S.D.’s of the average descent times of the others in cases 1 and 5.

Passing events 2, 3, and 6 in stair 4A involve the others having average descent times falling between the descent times of the passer and passed. In passing event 2, the descent times of the passer and the passed are not within three S.D.’s of the average descent time of the others. In passing event 3, the descent times of the passer and passed are not within two S.D.’s of the average descent time of the others. In passing event 6, the descent times of passer and passed are not within nine S.D.’s of the average descent time of the others.

Within stair 4B, five of the six events involve others requiring similar descent times as the passers. These events are events 1, 2, 3, 5, and 6. The p-values between the passer average descent time and the other average descent time are 0.28 and 0.58 for events 1 and 6, respectively. Thus, the two samples travel with the same average descent time. In event 1, the descent time of the occupant who is passed is not within 20 S.D.’s of the average descent time of the others, and in event 6, the descent time of the passed occupant is not within eight S.D.’s of the average descent time of the others. For events 2, 3, and 5, the passer descent times are within one S.D. of the average descent times of the others. The descent times of those passed, however, are not within six S.D.’s for events 2 and 3, and not within four S.D.’s for event 5.

Event 4 in stair 4B contains others who travel with a significantly different average descent than both the passer and passed. The others in event 4 travel with a lower descent time than the passer. The passer’s descent time is not within two S.D.’s of the average descent time of the others, and the descent time of those passed is not within six S.D.’s. This is the only passing event that is observed in the analysis where the others have a lower average descent time than the passer.

5.3.2.2 Building 5 Stairs

There are a total of 24 passing events analyzed in the Building 5 stairwells. 15 events are analyzed from stair 5A and 9 events are analyzed from 5B. The Building 5 stairwell passing descent time data is shown in Tables 5-24 and 5-25 for stairs 5A and 5B, respectively. As with the Building 4 data, similarity between the average descent time of the others and the descent times of individual passer and passed is based on the average plus or minus two standard deviations. For samples containing more than one individual, t-tests are used to calculate p-values to determine similarity in average descent times.

Within stair 5A, 11 of the 15 observed passing events involve single-person passing. Two events (5 and 15) involve two single-person passes that occur one after the other. Thus, in both cases, the first and third occupants pass the second and fourth occupants sometime during the descent between adjacent camera views.

Three events (3, 6, 12) involve an occupant passing multiple individuals ranging from two to four people. Event 7 involves two individuals passing one person.

Within stair 5B, five of the nine events involve single-person passing. These events are 1, 5, 7, 8, and 9.

The other four events involve not only multiple people passing one person, but multiple people being passed by a single person. Event 2 involves one person passing two people directly followed by a person passing the second person passed by the first passer.[5] Event 3 involves a person passing two people directly followed by another person passing two people. The first occupant passes the second and fourth occupants, and the third occupant passes the fourth and

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[5] For clarification, refer to Appendix F for a graphical representation of the data.

Pass Event	Description	# of Others	Passer Des. Time (s)	Passed Des. Time (s)	Other Des. Time (s)	p-value
1	1 pass 1	4	52.78	55.78	52.88 (0.4)	
2	1 pass 1	27	50.82	52.45	52.25 (0.39)	
3	1 pass 2	9	44.41	47.98 (0.1)	48.03 (0.17)	0.65
4	1 pass 1	8	45.85	48.89	46.1 (0.36)	
5	1 pass 1 x2	1	44.58 (0.1)	46.28 (0)	46.38	0.03
6	1 pass 2	12	42.04	46.89 (0.33)	46.79 (0.52)	0.76
7	2 pass 1	1	45.32 (0.23)	48.82	46.42	
8	1 pass 1	13	45.18	47.95	47.85 (0.35)	
9	1 pass 1	3	43.94	45.11	43.78 (0.54)	
10	1 pass 1	7	37.5	38.5	37.43 (0.29)	
11	1 pass 1	11	37.07	39.7	37.51 (0.57)	
12	1 pass 4	4	25.86	37.44 (0.45)	37.06 (0.22)	0.2
13	1 pass 1	2	36.76	37.84	37.24 (0.23)	
14	1 pass 1	3	36.47	37.54	37.55 (0.2)	
15	1 pass 1 x2	4	42.11 (0.42)	44.04 (0.38)	41.54 (0.39)	0.26 (pass:oth) 0.01 (passd:oth)

Table 5-24: Descent Times of Passing Events in Stair 5A

Pass Event	Description	# of Others	Passer Des. Time (s)	Passed Des. Time (s)	Other Des. Time (s)	p-value
1	1 pass 1	3	41.64	43.42	42.72 (0.23)	
2	1 pass 2, 1 pass 1	3	27.25 (0.92)	30.84 (0.05)	28.59 (0.3)	0.27 (pass:oth) 0.004 (passd:oth)
3	1 pass 2 x2	4	38.56 (0.21)	43.15 (1.24)	40.73 (0.42)	0.001 (pass:oth) 0.07 (passd:oth)
4	1 pass 2	5	39.51	42.05 (0.37)	41.56 (0.4)	0.27
5	1 pass 1	2	41.55	42.54	42.53 (0.02)	
6	2 pass 1	6	37.11 (0.48)	39.47	38.3 (0.4)	0.13
7	1 pass 1	7	40.54	42.98	42.15 (0.68)	
8	1 pass 1	2	41.85	43.61	43.22 (0.28)	
9	1 pass 1	2	43.98	45.88	44.5 (0.33)	

Table 5-25: Descent Times of Passing Events in Stair 5B

fifth occupants. Event 4 involves one person passing two people, and event 6 involves two people passing one person.

In stair 5A, there are six events where the descent times of the others are similar to the descent time of the passer. These events are 1, 4, 9, 10, 11, and 15. During passing events 1, 4, 9, 10, and 11, the passer’s descent time is within one S.D. of the average descent times of the others. For events 1 and 4, the descent times of those passed are not within seven S.D.’s. For event 9, the descent time of those passed is not within two S.D.’s. During events 10 and 11, the descent time of those passed is not within three S.D.’s. Event 15 involves multiple passers, passed, and others, thus t-tests are performed. P-values of 0.26 and 0.01 are calculated between passer and other and passed and other, respectively. This infers that the others require the same amount of time to descend as the passers, and require less time to descend than those passed.

Unlike the passing events in Building 4 stairs, there are events in Building 5 stairs where the others require the same amount of time to descend as those passed. Within stair 5A, seven events involve the others requiring the same amount of time to descend as those passed. These events are 2, 3, 5, 6, 8, 12, and 14. For event 2, the descent time of the person passed is within one S.D. of the average descent time of the 27 others, while the descent time of the passer is not within three S.D.’s. For event 3, the p-value between the two passed and the nine others is 0.65, thus inferring the same descent time, while the descent time of the passer is not within 21 S.D.’s of the average descent time of the others. For event 5, the descent time of the other is not within 17 S.D.’s of the average descent time of the passers, while the difference between the other’s descent time and the average of the two passed is 0.1 s. For event 6, the p-value between the others and those passed is 0.76, inferring the same descent time, while the descent time of the passer is not within nine S.D.’s of the average of the others. During event 8, the descent time of the person passed is within one S.D. of the others, while the passer’s descent time is not within seven S.D.’s of the others. During event 12, the p-value between the four passed and the four others is 0.2, inferring the same descent time, while the passer’s descent time is not within 50

S.D.'s of the others. Finally, for event 14, the descent time of the person passed is within one S.D. of the others, while the passer's descent time is not within five S.D.'s of the others.

Within stair 5A, there are two instances of the others descending with a time in between the descent times of the passer and those passed. During event 7, the other's descent time is not within four S.D.'s of the two passers, and is 2.4 s lower than the descent time of the person passed. For event 13, both the passer's descent time and the descent time of the person passed are not within two S.D.'s of the average of the others.

Within stair 5B, there are three instances where the others require the same amount of time to descend as the passer. These events are 2, 6, and 9. During event 2, p-values of 0.27 and 0.004 are calculated between passer and other and between passed and other, respectively. Thus, the others require the same amount of time to descend as the passers, but require less time to descend than those passed. For event 6, a p-value between two passers and six others is calculated as 0.13, inferring the same descent time. However, the descent time of the person passed in event 6 is not within two S.D.'s of the average of the others. During event 9, the descent time of the passer is within two S.D.'s of the average of the others, while the descent time of the person passed is not within four S.D.'s of the average of the others.

Like stair 5A, stair 5B also contains passing events where the others require the same amount of time to descend as those passed. This type of passing situation occurs five times in stair 5B: events 3, 4, 5, 7, and 8. For event 3, the p-values are 0.07 between others and those passed and 0.001 between others and passers. Thus, the others travel with a descent time similar to the descent time of those passed, but require more time to descend than the passers. For event 4, the p-value is 0.27 between the others and those passed, inferring the same descent time. However, the passer's descent time in event 4 is not within five S.D.'s of the average of the others. During event 5, the passer's descent time is not within 48 S.D.'s of the others, but the descent time of the person passed is within one S.D. of the others. For event 7, the descent time of the person passed is within two S.D.'s of the others, but the passer's descent time is not within two S.D.'s of the others. For event 8, the descent time of the person passed is within two S.D.'s of the others, but the passer's descent time is not within four S.D.'s of the others.

Event 1 is the only passing event in stair 5B where the others travel with a descent time in between that of the passer and passed. The passer's descent time is not within four S.D.'s of the average descent time of the others, and the descent time of the person passed is not within three S.D.'s of the others.

5.3.2.3 Discussion

Within Building 4 stairwells, the others directly following a passing event require descent times similar to or less than the passer's descent time in 75% of the passing events observed. In 25% of the observed passing events from Building 4 stairs, the others require a time to descend that fell in between the descent times of the passer and those passed.

Of the passing events that involve the others requiring descent times similar to or less than the passer's descent time, 67% involves single-person passing, 11% involves a person passing two people, and 22% involves multiple people passing a single person. Of the passing events where the others require a descent time that falls in between the passer and passed descent times, all of the events involve single-person passing.

In Building 5 stairwells, others directly following a passing event require descent times similar to the passer's descent time in approximately 37% of the passing events observed. In 50% of the observed passing events in Building 5 stairs, the others require a time to descend that is similar to the descent time of those passed. And, in 13% of the observed passing events, the others require a time to descend that falls in between the descent times of the passer and those passed.

Of the passing events in which the others' descent times are similar to the passer's descent time, 67% involves single-person passing, 11% involves two people passing 1 person, and 22% involves multiple passing events occurring in a row. Of the events where the others require the same amount of time to descend as those passed, 50% involves single-person passing, 33% involves one person passing multiple people, and 17% involves multiple passing events occurring in a row. Of the passing events where the others require a descent time that falls in between the passer and passed descent times, 67% involves single-person passing, while 33% involves two people passing one person.

Comparisons between the descent times of the others directly following a passing event and the passer/passed descent times result in relatively different trends within the different building stairwells. While no passing event observed in Building 4 involves the others requiring the same amount of time to descend as those passed, the majority of the events in Building 5 stairs do.

5.4 Merging Behavior and Effects

5.4.1 Merger Demographics

As with the passing behavior demographic analysis, an examination of who merges and who allows merging is done for the four stairwells. The genders and lanes of those involved with merging situations on-camera are presented. Only genders of multi-person mergers are presented because single-person mergers are assumed to only be based on where they merge and not based on gender. Pie charts showing the results of the merging behavior demographics presented in this section are located in Appendix G.

Before presenting the results, it is important to note that the gender demographics within this section should be used for information purposes only and not for establishing definitive conclusions from the data provided. The results could solely be due to the position of occupants in the stair when the merging occurs and may not be due directly to the genders of those involved with the merger phenomenon. Deference behavior associated with gender is a topic that needs further research, but with the data provided, it is not analyzed here.

Definitive conclusions can, however, result from an examination of exit lane usage by those who merge and those who allow the merge to establish where people are within the stairwell before and after a merger. The effects that exit lane usage of those involved with a merger has on the descent of the population following the phenomenon is a topic for further research.

5.4.1.1 Building 4 Stairs

The results of the single-person merging gender analysis for stairwells 4A and 4B are presented in Tables 5-26 and 5-27. Table 5-26 shows the genders of those who allowed a merge, while Table 5-27 shows which genders merged with which.

Gender	4A	4B	% of Total	Normalized %
Male Allowed Merge	12	14	50	47
Female Allowed Merge	15	11	50	53
Total	27	25		

Table 5-26: Building 4 Single-Person Merges by Gender

In stair 4A, there are more females who allow a merge than there are males who allow a merge; however, in stair 4B, there are more males who allow a merge than there are females who allow a merge. Looking at both stairs in Building 4 for single-person merging, there are slightly more females who allow a merge than there are males who allow a merge.

Gender	4A	4B	Total	% of Total
M merge w/ M	9	9	18	35
M merge w/ F	9	4	13	25
F merge w/ M	3	5	8	15
F merge w/ F	6	7	13	25

Table 5-27: Building 4 Single-Person Merges: Gender Scenarios

Table 5-27 shows the breakdown of who merges in front of who in stairs 4A and 4B. Examining all of the Building 4 single-person merges, the merger situation that occurs the most is male merging in front of male, which occurs 35% of the time. The next most prevalent single-person merger scenario is split between male merging in front of female and female merging in front of female, which both occurs 25% of the time. The least prevalent single-person merger situation in Building 4 is female merging in front of male, which occurs 15% of the time.

The results of the exit lane analysis of the single-person merging in Building 4 are presented in Table 5-28. In both stairs 4A and 4B, there are more people merging in the outer lane than the inner or middle lanes, as well as more people in the outer lane allowing merges than people allowing a merge in the inner or middle lanes. In both stairs, there are no people in the inner lane who merge. Out of the total single-person mergers occurring on-camera in Building 4, 91% of those who merge do so in the outer lane, while 9% of those who merge are in the middle lane. Out of those individuals allowing a single-person merge, 13% travel in the inner lane, 23% travel in the middle lane, and 64% travel in the outer lane.

Exit Lane	4A	4B	% of Total
Inner Merger	0	0	0
Middle Merger	4	1	9
Outer Merger	24	24	91
Total	28	25	
Inner Allowed Merge	2	5	13
Middle Allowed Merge	8	4	23
Outer Allowed Merge	18	16	64
Total	28	25	

Table 5-28: Building 4 Single-Person Merges by Exit Lane

The results of the multiple-person merging gender analysis for stairwells 4A and 4B are presented in Tables 5-29 and 5-30. Table 5-29 shows the genders of those who merged and those who allowed a merge, while Table 5-30 shows which genders merged with which. In 4A, the number of individuals who merged during a multi-person merger ranges from two to seven. In 4B, the number of occupants who merged during a multi-person merger ranges from two to four.

Gender	4A	4B	% of Total	Normalized %
Male Merger	22	20	40	37
Female Merger	37	26	60	63
Total	59	46		
Male Allowed Merge	10	10	51	48
Female Allowed Merge	11	8	49	52
Total	21	18		

Table 5-29: Building 4 Multi-Person Merges by Gender

For multi-person mergers in Building 4 stairwells, there are more female mergers than male mergers. As with the single-person merger analysis, there is approximately the same number of males who allow a merger as there are females who allow a merger.

Gender	4A	4B	Total	% of Total
All M merge w/ M	1	3	4	11
All M merge w/ F	0	2	2	5
All F merge w/ M	2	3	5	14
All F merge w/ F	3	3	6	16
Mix merge w/ M	6	4	10	27
Mix merge w/ F	7	3	10	27

Table 5-30: Building 4 Multi-Person Merges: Gender Sequences

Table 5-30 shows the breakdown of gender sequences for multi-person merges in stairs 4A and 4B. The groups of people merging are separated into single-gender mergers and mixed-gender mergers. Examining all of the Building 4 multi-person merges, the merger situation that occurs the most is split between mixed-gender groups merging in front of males and mixed-gender groups merging in front of females, each occurring 27% of the time. The next most prevalent multi-person merger scenario is all females merging in front of a female, which occurs 16% of the time. After that, the most prevalent scenarios are females merging in front of male (14%), males merging in front of male (11%), and males merging in front of female (5%).

Combining the mixed-gender merger numbers, and the single-gender merger numbers, mixed-gender merger groups account for approximately 54% of the multi-person merging scenarios, while all-female merger groups account for 30% and all-male merging groups account for 16%.

The results of the exit lane analysis of the multi-person merging in Building 4 are presented in Table 5-31. As with the single-person merging analysis, in both stairs 4A and 4B, there are more people merging in the outer lane than the inner or middle lanes, as well as more people in the outer lane allowing merges than people allowing a merge in the inner or middle lanes. Unlike the single-person merging analysis, there are some merging individuals who are in the inner lane.

Out of the total multi-person mergers occurring on-camera in Building 4 stairs, 81% of those who merge do so in the outer lane, while 13% of those who merge are in the middle lane and 6% of those who merge are in the inner lane. Out of those individuals allowing a multi-person merge, 5% travel in the inner lane, 28% travel in the middle lane, and 67% travel in the outer lane.

Exit Lane	4A	4B	% of Total
Inner Merger	4	2	6
Middle Merger	10	4	13
Outer Merger	47	37	81
Total	61	43	
Inner Allowed Merge	2	0	5
Middle Allowed Merge	6	5	28
Outer Allowed Merge	14	13	67
Total	22	18	

Table 5-31: Building 4 Multi-Person Merges by Exit Lane

5.4.1.2 Building 5 Stairs

The results of the single-person merging gender analysis for stairwells 5A and 5B are presented in Tables 5-32 and 5-33. Table 5-32 shows the genders of those who allowed a single person to merge, while Table 5-33 shows which genders merged with which.

Gender	5A	5B	% of Total	Normalized %
Male Allowed Merge	24	21	54	48
Female Allowed Merge	21	17	46	52
Total	45	38		

Table 5-32: Building 5 Single-Person Merges by Gender

In the Building 5 stairs, there are slightly more females who allow a single-person merge than there are males who allow a single-person merge.

Gender	5A	5B	Total	% of Total
M Merge w/ M	9	18	27	36
M Merge w/F	11	11	22	30
F Merge w/ M	10	3	13	17
F Merge w/ F	7	6	13	17

Table 5-33: Building 5 Single-Person Merges: Gender Scenarios

Table 5-33 shows the breakdown of who merges in front of who in stairs 5A and 5B. Examining all of the Building 5 single-person merges, the merger situation that occurs the most is male merging in front of male, which occurs 36% of the time. The next most prevalent single-person merger scenario is male merging in front of female, which occurs 30% of the time. The least prevalent single-person merger situation in Building 5 is split between female merging in front of male and female merging in front of female, which each occurs 17% of the time.

The results of the exit lane analysis of the single-person merging in Building 5 are presented in Table 5-34. In both stairs 5A and 5B, there are more people merging in the outer lane than the inner or middle lanes, and more people in the inner lane allowing merges than people allowing a merge in the outer or middle lanes. Out of the total single-person mergers occurring on-camera in Building 5, 95% of those who merge do so in the outer lane, with 4% of those who merge being in the middle lane and 1% of those who merge being in the inner lane. Out of those individuals allowing a single-person merge, 63% travel in the inner lane, 11% travel in the middle lane, and 26% travel in the outer lane.

Exit Lane	5A	5B	% of Total
Inner Merger	0	1	1
Middle Merger	3	0	4
Outer Merger	43	37	95
Total	46	38	
Inner Allowed Merge	30	24	63
Middle Allowed Merge	7	2	11
Outer Allowed Merge	10	12	26
Total	47	38	

Table 5-34: Building 5 Single-Person Merges by Exit Lane

The results of the multi-person merging gender analysis for stairwells 5A and 5B are presented in Tables 5-35 and 5-36. Table 5-35 shows the genders of those who merge and those who allow a merge, while Table 5-36 shows which genders merge with which. In 5A, the number of individuals who merge during a multi-person merger ranges from two to six. In 5B, the number of occupants who merge during a multi-person merger ranges from two to four.

Gender	5A	5B	% of Total	Normalized %
Male Merger	38	35	50	45
Female Merger	40	32	50	55
Total	78	67		
Male Allow Merge	16	15	53	48
Female Allow Merge	15	12	47	52
Total	31	27		

Table 5-35: Building 5 Multi-Person Merges by Gender

For multi-person mergers in the Building 5 stairwells, there are more female mergers than male mergers. As with the single-person merger analysis, there are slightly more females who allow a merge than there are males who allow a merge.

Gender	5A	5B	Total	% of Total
All M merge w/ M	2	4	6	12
All M merge w/ F	3	5	8	15
All F merge w/ M	2	6	8	15
All F merge w/ F	2	1	3	6
Mix merge w/ M	9	5	14	27
Mix merge w/ F	7	6	13	25

Table 5-36: Building 5 Multi-Person Merges: Gender Sequences

Table 5-36 shows the breakdown of who merges in front of who for multi-person merges in stairs 5A and 5B. As with the Building 4 analysis, groups of people merging are separated into single-gender mergers and mixed-gender mergers.

Examining all of the Building 5 multi-person merges, the merger situation that occurs the most is mixed-gender groups merging in front of males, which occurs 27% of the time. The next most prevalent multi-person merger scenario is mixed-gender groups merging in front of females, which occurs 25% of the time. The next most prevalent scenarios are split between all-male groups merging in front of a female and all-female groups merging in front of a male, which both occur 15% of the time. The least prevalent multi-person merger situations are single-gender groups merging in front of the same gender. All-male groups merging in front of a male occurs 12% of the time, and all-female groups merging in front of a female occurs 6% of the time.

Combining the mixed-gender mergers and the single-gender mergers, mixed-gender merger groups account for approximately 52% of the multi-person merging scenarios, while all-female merger groups account for 21% and all-male merger groups account for 27%.

The results of the exit lane analysis of the multi-person merging in Building 5 are presented in Table 5-37. As with the single-person merging analysis in stairs 5A and 5B, there are more people merging in the outer lane than the inner or middle lanes. However, the lanes of people who allow multi-person mergers are different from those of the single-person mergers. From the single-person merging analysis, the majority of those who allow a merge descend in the inner lane. However, with the multi-person merging, the majority of those who allow a merge are split between the inner and outer lanes. There are 28 instances of an occupant in the inner lane allowing a multi-person merge and 27 instances of an occupant in the outer lane allowing a multi-person merge.

Out of the total multi-person mergers occurring on-camera in building 5, 77% of those who merge do so in the outer lane, while 9% of those who merge are in the middle lane and 14% of those who merge are in the inner lane. Out of those individuals allowing a multi-person merge, 47% travel in the inner lane, 8% travel in the middle lane, and 45% travel in the outer lane.

Exit Lane	5A	5B	% of Total
Inner Merger	9	12	14
Middle Merger	8	6	9
Outer Merger	68	49	77
Total	85	67	
Inner Allow Merge	15	13	47
Middle Allow Merge	3	2	8
Outer Allow Merge	15	12	45
Total	33	27	

Table 5-37: Building 5 Multi-Person Merges by Exit Lane

5.4.1.3 Discussion

A comparison between the results of the merging demographic analyses in the stairwells of Building 4 and Building 5 is presented to determine any trends that are similar across the two buildings. Because the sample size is so small (only for two buildings), the similar trends presented must be verified through more research in other high-rise office building stairwells.

Within both the Building 4 and Building 5 stairwells, the majority of single-person mergers merge in the outer lane. Also, there are slightly more females who allow a single person to merge than there are males who allow a single person to merge. Also, within both buildings' stairwells, the single-person merging scenario that occurs most often is a single male merging in front of a male, and the single-person merging scenario that occurs least often is a single female merging in front of a male.

When examining multi-person merging, within both buildings' stairwells there are more females who merge with multiple people than there are males who merge with multiple people. Also, within both buildings' stairwells, there are slightly more females who allow multiple people to merge than males who allow multiple people to merge. Within both buildings, the majority of mergers who merge with multiple people do so in the outer lane. Also, the multi-person merging scenario that occurs the most in both buildings is when a mixed gender group merges in front of a male.

5.4.2 Merging Effects on Flows

To explore the possible effects on occupants descending the stair that mergers may cause, a flow analysis is done for sections of stairs 4A, 4B, 5A, and 5B where there is a continuous flow and sustained merging. First, a flow test is performed on sections of the stairs where there is no merging with only continuous flow emanating from either the stair or the floor to act as a control for the analysis. Then, possible merging effects are examined by comparing the inflows of two merging streams emanating from the stair and floor with the outflow of the combined stair and floor streams. Because the flows are calculated based on enter and exit times of the occupants, no sections of the stairwell are analyzed where queuing effects are present.

5.4.2.1 Non-Merging Flows

To act as a control for the merging flow analysis, sections of the stairs where no merging takes place are analyzed and presented in the following section. Non-merging flows comprise either occupants solely coming from the stairs, or occupants solely coming from the floor. Non-merging flows are found to occur towards the latter portions of the evacuation on the lower floors where the flow is mostly comprised of stair occupants descending from higher floors. During early portions of the evacuation, non-merging flows are found on most floors, but usually have fewer occupants than the latter non-merging stair flow. Early-evacuation non-merging flows are comprised of either stair or floor occupants depending on which group establishes the flow first on each particular camera.

The flow of occupants both at the enter point and exit point of the floors is calculated to compare the two values. The theory is that non-merging individuals act as fluid particles in a pipe, thus the flow in is expected to equal the flow out. The inflows and outflows of people coming from the stair and people coming from the floor are shown in Figures 5-17 and 5-18.

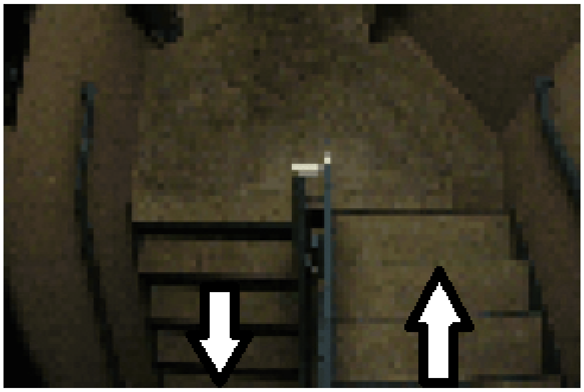


Figure 5-17: Inflow and Outflow of Stair Occupants

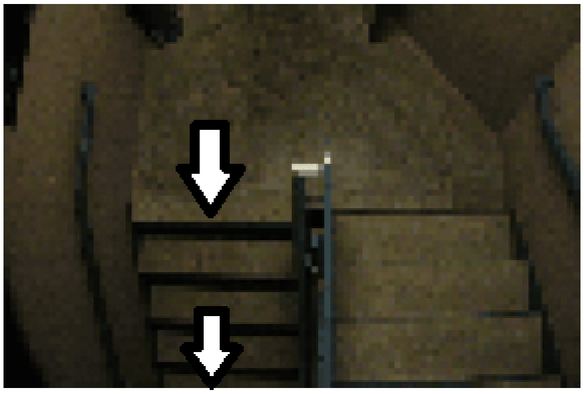


Figure 5-18: Inflow and Outflow of Floor Occupants

The following table shows the enter and exit order of a flow of 16 floor occupants on the 9th floor in stair 5A. To examine the inflows and outflows of the occupants shown in Table 5-38, flows are calculated at 5 s time intervals (with the exception of the last time period). Table 5-39 shows the results of this analysis with the ratio of outflow to inflow given in the last column. Figure 5-19 is the plot of the inflows and outflows at the 5 s time intervals. The flows shown in Figure 5-19 correspond to the number of people passing the enter and exit point in the preceding 5 s time period.

Enter Order	Enter Time (s)	Exit Order	Exit Time (s)
300	0	300	0
299	1.43	299	1.24
297	4.84	297	4.78
313	6.1	313	5.38
306	9.71	306	9.15
307	11.08	307	10.45
309	12.01	309	11.85
308	13.14	308	12.62
311	13.98	311	13.78
333	15.71	333	15.72
320	17.28	320	17.42
322	18.58	322	18.92
339	19.92	339	20.09
341	21.32	341	21.69
340	23.05	340	23.09
342	24.82	342	25.56

Table 5-38: Enter and Exit Order of Floor Occupants on 9th Floor of 5A

Time Period (s)	# Enter	Inflow (persons/s)	# Exit	Outflow (persons/s)	Outflow : Inflow Ratio
0 to 5	3	0.62	3	0.63	1.02
5 to 10	2	0.55	2	0.53	0.96
10 to 15	4	1.38	4	1.20	0.87
15 to 20	3	1.05	3	0.94	0.90
20 to 26	4	0.82	4	0.73	0.89

Table 5-39: Inflows and Outflows of Floor Occupants on 9th Floor of 5A

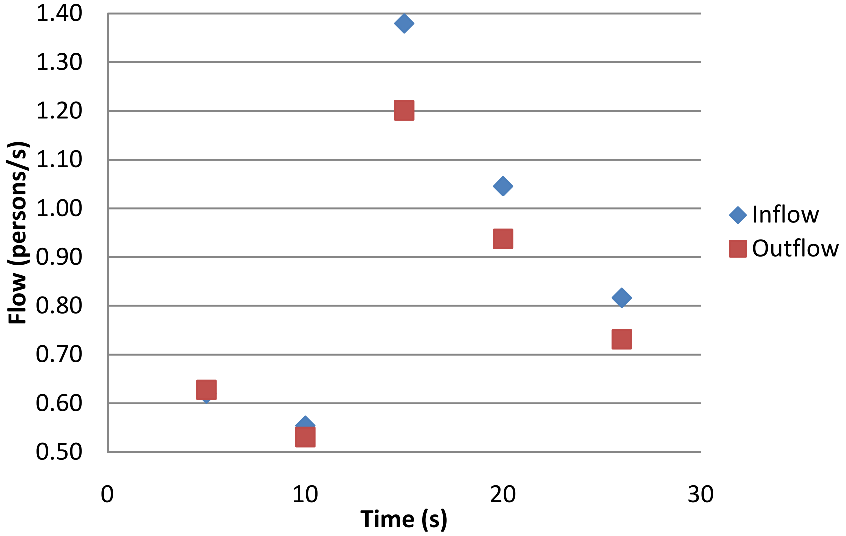


Figure 5-19: Inflows and Outflows of Floor Occupants on 9th Floor of 5A

Table 5-39 and Figure 5-19 show that the inflows and outflows of the floor occupants on the 9th floor in 5A are similar. The inflows and outflows are relatively equal, especially considering the data used in the analysis. A slight pause or slight increase in speed from one step to another by an occupant(s) could cause small changes in the values calculated for inflows and outflows.

Next, a flow of 16 stair occupants on the 6th floor in stair 4B is analyzed. Table 5-40 shows the enter and exit order of these occupants as they descended past the 6th floor camera. Again, inflows and outflows are calculated every 5 s with respect to the first occupant (with the exception of the last time period). Table 5-41 and Figure 5-20 show the results of the flow analysis.

Enter Order	Enter Time (s)	Exit Order	Exit Time (s)
280	0	280	0
281	2.07	281	2.4
282	4.67	282	4.41
283	6.84	283	7.01
285	8.67	284	8.88
284	8.84	285	8.94
286	11.21	286	10.68
287	12.91	287	12.48
288	14.61	288	14.75
289	16.08	289	16.25
290	17.88	290	18.29
291	19.45	291	19.89
292	21.89	292	21.86
293	24.42	293	23.73
294	26.02	294	25.59
295	26.86	295	26.33

Table 5-40: Enter and Exit Order of Stair Occupants on 6th Floor of 4B

Time Period (s)	# Enter	Inflow (persons/s)	# Exit	Outflow (persons/s)	Outflow : Inflow Ratio
0 to 5	3	0.64	3	0.68	1.06
5 to 10	3	1.50	3	1.55	1.03
10 to 15	3	0.88	3	0.74	0.84
15 to 20	3	0.89	3	0.82	0.92
20 to 27	4	0.80	4	0.89	1.11

Table 5-41: Inflows and Outflows of Stair Occupants on 6th Floor of 4B

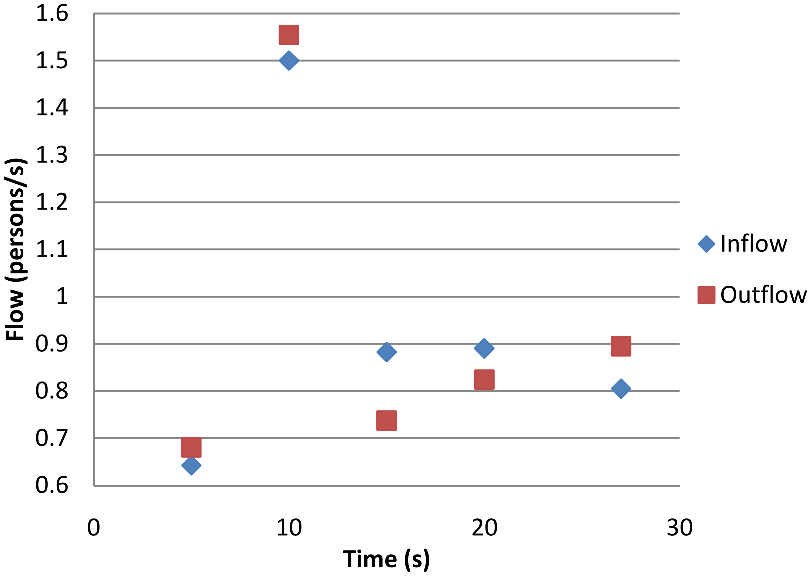


Figure 5-20: Inflows and Outflows of Stair Occupants on 6th Floor of 4B

As with the flow of floor occupants on floor 9 of stair 5A, the inflows and outflows of the stair occupants on floor 6 of stair 4B are similar. Again, the slight differences between the two calculated values are attributable to the data used.

5.4.2.2 Merging Flows

In Section 5.4.2.1, when non-merging occupants descend the stairs, the flow coming into the camera view is approximately equal to the flow leaving the camera view. An analysis of the effects that mergers may cause on the outflows of occupants involved is presented in this section.

In the merging flow analysis, there are two inflows; one stemming from the stairs and one from the floor. These flows then converge in the merger region (usually located on the landing) and continue the descent down the stairs as one unified outflow. Using the fluid mechanics analogy, the sum of the two inflows is expected to equal the outflow.

Figure 5-21 shows the general locations of the two inflows and the outflow within the stairwells. The red arrow is the outflow of the merger and the two blue arrows are the inflows to the merger. The hydraulic model of the SFPE Handbook assumes a laminar flow of people down the stair. The model assumes that the entire effective width of the stair is utilized by occupants during their descent. A merger, therefore, should not affect the inflows of the stair and floor occupants because two lanes can be used. Thus, according to theory, the sum of the inflows should equal the outflow if no queue forms within the camera view.

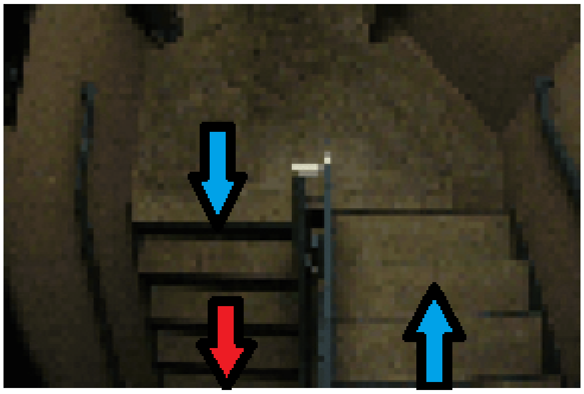


Figure 5-21: Inflows (Blue Arrows) and Outflow (Red Arrow) of Merging Flows

The results of an example of the merging flow analysis is shown in Table 5-42 and Figure 5-22 for stair 5B on floor 5. Only those merger events that occur on camera are considered for the merging flow analyses presented in this section.

From the results presented in Table 5-42 and Figure 5-22, it is apparent that the outflows of the merging occupants do not equal the sum of their inflows. In fact, for two time periods (20-30 s, 50-65 s) the outflow is slightly less than one of the inflows; in one case, slightly less than the floor inflow, in the other, slightly less than the stair inflow. During each time period, the outflow of the merging streams is less than the sum of the two merging inflows. The average of the ratios given in Table 5-42 is 0.70 plus or minus 0.06 (error given as sample S.D.). This indicates that the observed outflow of this section in stair 5B is on average 70% of the total inflow of the two merging streams. Thus, the outflow is 30% less than the sum of the two inflow streams.

Time Period (s)	Floor Inflow (persons/s)	Stair Inflow (persons/s)	Total Inflow (persons/s)	Outflow (persons/s)	Outflow : Inflow Ratio
0 to 10	0.63	0.84	1.47	1.00	0.68
10 to 20	0.57	0.90	1.47	0.94	0.64
20 to 30	1.02	0.58	1.59	1.01	0.64
30 to 40	0.56	1.03	1.59	1.22	0.77
40 to 50	0.49	0.63	1.12	0.86	0.77
50 to 65	0.38	0.94	1.32	0.91	0.69

Table 5-42: Merging Flow Analysis on Floor 5 of Stair 5B

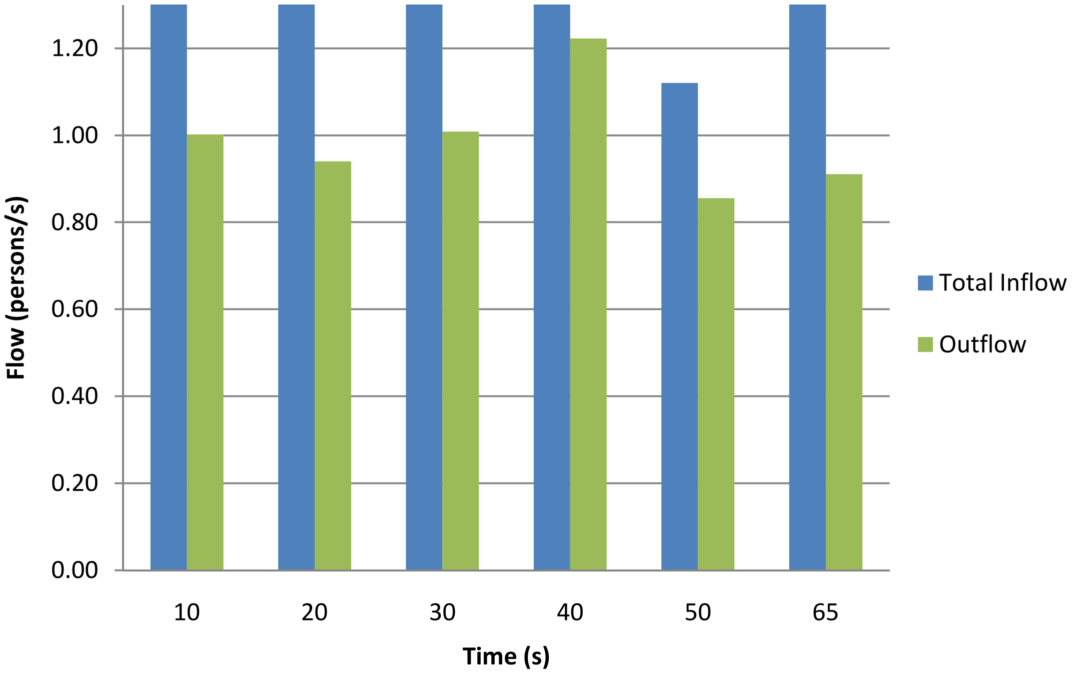


Figure 5-22: Merging Flow Analysis on Floor 5 of Stair 5B

The same type of merging analysis is done for every floor in stairs 4A, 4B, 5A, and 5B where sustained merging occurs during non-queuing situations. Sustained merging in the current analysis occurs when each time period used to calculate the respective flows contains more than one stair occupant and more than one floor occupant in the outflow.

The results of the merging flows analyses are shown in Tables 5-43 to 5-46 for all of the on-camera merging situations observed in stairs 4A, 4B, 5A, and 5B, respectively. These tables include the total inflow, which flow theory predicts to be the ideal outflow, and the ratio of outflow to inflow. The bar graphs of these results with the specific time periods used are presented in Appendix H.

Floor Inflow (persons/s)	Stair Inflow (persons/s)	Total Inflow (persons/s)	Outflow (persons/s)	Outflow : Inflow Ratio
0.76	0.52	1.28	0.75	0.58
0.88	0.99	1.87	0.46	0.25
1.39	0.68	2.07	0.60	0.29
0.38	0.36	0.73	0.63	0.86
0.50	0.58	1.07	0.58	0.54
0.31	0.30	0.61	0.58	0.94
0.92	0.79	1.71	0.68	0.40
0.47	0.50	0.97	0.77	0.79
0.52	0.67	1.19	0.75	0.63
0.70	1.16	1.85	0.74	0.40
0.86	0.42	1.28	0.78	0.61
0.37	0.48	0.86	0.57	0.67
0.38	0.63	1.00	0.81	0.81
0.21	0.40	0.62	0.61	0.99
0.31	0.75	1.06	0.73	0.69
0.44	0.53	0.98	0.92	0.94
1.13	0.56	1.69	0.62	0.37

Table 5-43: Merging Flows of Stair 4A

Floor Inflow (persons/s)	Stair Inflow (persons/s)	Total Inflow (persons/s)	Outflow (persons/s)	Outflow : Inflow Ratio
0.50	0.32	0.82	0.62	0.76
0.93	1.54	2.47	0.45	0.18
0.92	0.54	1.46	0.87	0.60
0.57	0.43	1.00	0.77	0.77
0.53	0.92	1.45	0.78	0.54
0.51	0.77	1.28	0.75	0.59
0.48	0.51	0.98	0.80	0.81
0.75	0.62	1.37	0.73	0.53
0.74	0.62	1.36	0.66	0.49
1.32	0.86	2.18	0.85	0.39
1.05	1.46	2.51	0.82	0.33

Table 5-44: Merging Flows of Stair 4B

Floor Inflow (persons/s)	Stair Inflow (persons/s)	Total Inflow (persons/s)	Outflow (persons/s)	Outflow : Inflow Ratio
0.77	1.27	2.04	0.94	0.46
0.82	0.89	1.71	1.28	0.75
1.25	0.88	2.13	1.70	0.80
1.30	0.78	2.08	1.28	0.61
0.82	1.80	2.62	1.08	0.41
0.70	0.77	1.47	1.14	0.77
1.43	1.18	2.61	1.36	0.52
2.00	1.18	3.18	1.53	0.48
1.57	4.00	5.57	1.36	0.24
0.84	1.60	2.45	1.30	0.53
0.76	1.07	1.82	1.40	0.77
0.69	6.06	6.75	0.91	0.14
0.38	1.49	1.87	0.81	0.43
0.65	0.62	1.27	0.95	0.75
0.71	1.58	2.28	1.06	0.46
0.52	0.79	1.31	1.07	0.82
0.60	1.06	1.67	1.30	0.78

Table 5-45: Merging Flows of Stair 5A

Floor Inflow (persons/s)	Stair Inflow (persons/s)	Total Inflow (persons/s)	Outflow (persons/s)	Outflow : Inflow Ratio
0.44	0.45	0.88	0.67	0.76
2.50	0.67	3.17	0.71	0.22
0.46	0.92	1.38	1.25	0.90
1.36	0.94	2.30	0.99	0.43
0.63	0.84	1.47	1.00	0.68
0.57	0.90	1.47	0.94	0.64
1.02	0.58	1.59	1.01	0.63
0.56	1.03	1.59	1.22	0.77
0.49	0.63	1.12	0.86	0.76
0.38	0.94	1.32	0.91	0.69
0.59	1.58	2.16	0.83	0.38
0.74	0.83	1.58	0.88	0.56
0.78	0.95	1.72	1.27	0.74
0.67	0.59	1.26	1.15	0.91
0.63	0.80	1.43	0.94	0.65
0.71	1.30	2.01	1.13	0.56
0.76	0.34	1.10	0.85	0.77

Table 5-46: Merging Flows of Stair 5B

5.4.2.3 Discussion

From the preceding tables, it is evident that the ideal outflow that is predicted by flow theory is greater than the actual outflows observed in stairs 4A, 4B, 5A, and 5B. Out of all 62 merging events observed on-camera in the four stairs, every observed outflow is less than the sum of the stair and floor inflows.

The average of the ratios for stair 4A given in Table 5-43 is 0.63 plus or minus 0.24. The average of the ratios for stair 4B given in Table 5-44 is 0.54 plus or minus 0.20. Examining all of the merging flows in Building 4, the average ratio of outflow to total inflow is 0.60 plus or minus 0.22.

The average of the ratios for stair 5A given in Table 5-45 is 0.57 plus or minus 0.21. The average of the ratios for stair 5B given in Table 5-46 is 0.65 plus or minus 0.18. Examining all of the merging flows in Building 5, the average ratio of outflow to total inflow is 0.61 plus or minus 0.19.

From the results of the merging flows analysis, it is clear that the observed outflows downstream of a merger are typically less than the sum of the two incoming flows. Although there are some instances where the total inflow is close to the observed outflow, the majority of the observed outflows are less than the total inflow.

The outflow to total inflow ratios show that the flow after a merger is less than the sum of the two flows going into the merger. Thus, it seems that those interacting within the stair due to a merger move slower directly after the merger compared to before the merger. Despite there being enough room to move with two lanes, lower flows are experienced after a merger. This may be due to people on the stair slowing down or completely stopping to let merging occupants go before them.

Chapter 6: Conclusions and Future Research

6.1 The Role of Density

Using two methods to calculate density, speed vs. density graphs are created with the data from the stairwells of buildings 4 and 5. One method utilizes the average number of people on the landing, while the other utilizes the number of occupants on the landing when someone enters the landing. The average count of people assumes the level of crowdedness surrounding an individual has an impact on local movement speed, while the enter count assumes only the level of crowdedness in front of an individual has an effect on local movement speed.

The differing density calculation methods seem to have more of an impact on the data within the stairwells in Building 4 as opposed to the data from stairs in Building 5. The average count density method resulted in a speed vs. density R^2 of 0.33, while the enter count density method resulted in a speed vs. density R^2 of 0.28 for the Building 4 stair data. For the Building 5 stair data, both density calculation methods resulted in a speed vs. density R^2 of 0.10. These R^2 values not only show that differing density calculation methods can produce different results within stairwells in the same building, but that people movement in stairs of differing buildings can result in drastically different speed vs. density results even when utilizing the same density calculation methods.

The hydraulic model used in fire protection engineering regards density as the main contributor to the local movement speeds of individuals during an evacuation. Other than stair geometry, density is the only factor used in predicting the amount of time it takes a population to egress. Therefore, why are the speed vs. density R^2 values of the Building 4 and Building 5 egress data not only low, but drastically different?

One hypothesis is that human behavior phenomena are probable explanations for the low values. The hydraulic model fails to take into account the variability of human decision-making and the effects certain human interactions may have on local movement speeds of evacuating populations. Although it is impossible to create a model that considers the totality of the variability of human behavior, understanding the trends associated with certain phenomena will aid in the creation of better egress models.

Density is an important parameter in determining movement speed, but it is not the only factor that can affect the time it takes for a population to evacuate. This report focuses on three types of human behavior phenomena and the people movement trends observed for each one.

6.2 Platoon Movement

Platoons are defined as groups of individuals moving close to one another with the same type of flow pattern. Three types of platoon movement are identified at sections of the stairwell where no merging or queues occur: platoon elongation, compression, and equilibrium. Platoon elongation occurs when the descent times of the majority of members within the platoon increase from first person to last. Platoon compression occurs when the descent times of the majority of members within the platoon decrease from first person to last. Platoon equilibrium occurs when the majority of members within the platoon travel with the same descent time.

Platoons are separated based on exit time gaps in stair 4A, and sub-platoons are separated based on elongation, compression, and equilibrium descent time patterns. Average descent times of the platoons in 4A increase from platoon to platoon as shown in Figure 5-2. Similar trends are seen in the sub-platoons and their position in the overall platoon. Within each platoon identified for stair 4A, an alternating pattern between equilibrium and either elongation or compression is observed.

A fairly consistent trend is observed with the platoons in stair 4A involving where differing and similar average descent times are seen. Typically, when an elongating/compressing sub-platoon follows an equilibrium sub-platoon, the average descent times of the sub-platoons are significantly different. However, when an equilibrium sub-platoon follows an elongating/compressing sub-platoon, the average descent times of the sub-platoons are typically statistically similar.

The non-merging platoon analysis of stairwell 5A involves an identification of more platoons because platoons are separated not only by exit time gap, but also based on passing behavior as is done by Hoskins [36]. Sub-platoons within platoons containing no passing behavior are separated based on descent time pattern as is done in the stair 4A platoon analysis. However, for platoons containing passing behavior, sub-platoons are separated based on whether someone is a passer, is passed, or is not directly involved with a passing event (classified as "other").

Average descent times of the platoons in 5A display a pulsating pattern between increases and decreases that may be associated with passing behavior. Within each passing platoon, the average descent times of the passers are significantly different than the average descent times of those passed.

Platoons in stair 5A display an alternating trend between passing platoons and non-passing platoons. Platoons 1, 4, 6, 8, and 10 contain passing behavior, while platoons 2, 5, 7, 9, 11, 12, and 13 do not contain passing. Platoons 1 through 11 are determined to be spatially close based on the exit time gap at the 3rd floor landing. Platoon 3 is separated because it is identified as a one-person platoon.

Passing platoons 1 and 10 contain passers in both the inner and outer lanes, while the other passing platoons only contain passers in the inner lane. Other than platoons 2 and 11, non-passing platoons spatially close and adjacent to two passing platoons typically travel in equilibrium at a descent time similar to the others of the preceding passing platoon.

A trend of "others" within a passing platoon having similar descent times to either the passer or those passed is observed. Within passing platoons where multiple people are passed (i.e. the middle portion of platoon 1, platoons 4 and 8), the average descent time of the others directly following this pass is similar to the average of those passed. However, within passing platoons where only one person is passed (i.e. platoon 6), the others require the same amount of time to descend as the passer.

6.3 Passing Behavior

The Building 4 stairwells contain little passing compared to the Building 5 stairwells. A total of 43 passing events are observed in the Building 4 stairs, compared to a total of 231 passing events in Building 5 stairs. This difference in the frequency of passing phenomena may explain the different speed vs. density R^2 values observed in the different building stairwells. Perhaps less passing results in a more laminar flow of people which the hydraulic model can reasonably predict. However, because only two buildings are studied, future research is needed to explore this hypothesis.

An exploration of gender and exit lane demographics were used to show which occupants are more likely to be single or multi-person passers, as well as which occupants are more likely to be passed by a single person or multiple people.

In stairwells in both buildings, single-person passers typically travel in the inner and middle lanes, while those passed by a single person typically travel in the outer lane. Also, there are more females who pass multiple people than there are males who pass multiple people, and slightly more males passed by multiple people than there are females passed by multiple people in both building's stairwells. In both buildings, those passed by multiple people typically travel in the middle or outer lane. No definitive similarities or conclusions could be drawn regarding who passes who during single-person and multi-person passing scenarios.

An interesting trend in passing behavior is observed in the Building 5 data where many occupants who merge into the stair flow are passed by those who allow the merge by the time they reach the next camera view. In both stairs in Building 5, approximately 39% of the passers had allowed a person (or people) to merge in the preceding camera view before having passed the merger(s) by the next camera view. In both stairs in Building 5, approximately 35% of those passed had merged in the preceding camera view before having been passed by the next camera view. Future research is needed to determine whether this type of passing behavior is a common occurrence within high-rise stairwell evacuations.

While the majority of the others in Building 4 passing events require similar times to descend as the passer, the majority of the others in Building 5 passing events require similar times to descend as those passed. This may be a reason for the low speed vs. density R^2 values seen in the Building 5 stairwells. The majority of those following a passing event in Building 5 are not able to close the gap that forms between those passed and those following the passing event once the passer completes the pass. In Building 5 stairs, no instance of one person passing multiple people results in the others requiring the same amount of time to descend as the passer.

A definitive reason as to why certain occupants following a passing event require the same amount of time to descend as those passed, while others following an event require the same amount of time to descend as the passer cannot be determined based on the small sample size of the data in the analysis. Future research should explore this observation and investigate whether density plays a role in the determination of the local movement speeds of those following such passing events.

6.4 Merging Behavior

Although merger gender demographics are given in Chapter 5, the results should not be used to make definitive conclusions on the phenomenon. Gender and its role in deference behavior is an important area to explore; however, deference behavior was not explored due to the data limitations. Regardless, an important gender trend within the merger events in the Building 4 and Building 5 stairs was identified. Within stairs in both buildings, the majority of people who merge with multiple people are female. This suggests that more females begin evacuation with other people. This observation must be analyzed further through future research before a definitive claim is made; however, the observation could have an impact on pre-evacuation statistics regarding gender.

In the stairs in both buildings, there are slightly more females who allow a single person to merge than there are males who allow a single person to merge. Also, there are slightly more females who allow multiple people to merge than there are males who allow multiple people to merge.

Position within the stairwell seems to be more important than gender for merger events [28-30, 32]. An exit lane analysis of merger events found that the majority of occupants (both within single-person and multi-person mergers) merge in the outer lane of the stair. Occupants tend to merge in an area that does not cut off the stair flow to a great extent. Also, in both buildings, there are more inner lane mergers who merge with multiple people as opposed to merging individually. Virtually no single-person mergers enter the stair flow in the inner lane.

A flow analysis explored the effects that merging can have on those involved with the event. Using the fluid mechanics analogy, the sum of the stair inflow and the floor inflow should equal the observed outflow. However, the outflow to total inflow ratios showed that the outflow post-merger was approximately 60% of the sum of the stair and floor inflows. The flow after the merger event is less than the sum of the two incoming flows, which may be due to people in the stair slowing down or completely stopping to let others merge in front of them.

6.5 Suggestions and Future Research

6.5.1 Suggestions for NIST

Egress and human behavior research should have a clear goal before collecting raw data. Rather than collecting video data from multiple stairwells in multiple buildings at every other to every four floors, data can be collected at every landing over smaller sections of the stairwells. A smaller more in-depth view of human movement is beneficial because an understanding of the movement dynamics is more easily observed. When video data is only collected at every other to every four floors, many assumptions must be made over those sections where there is not a camera. The majority of certain types of movement phenomena, such as sudden stoppages or lane-switching, are not able to be viewed which may have significant impacts on the results.

Video cameras should not only be placed in the stairwell, but within the office or corridor leading into the stairwell on certain floors. People movement into the stairwell is just as important as people movement within the stairwell with regards to the merging process. Also, pre-evacuation times and social groups before the stairwell descent are important areas of future research where data can be collected by video cameras that are placed outside of the stair towards the landing door.

It is extremely important that the spreadsheet data taken from the raw video footage be collected by the same individuals, or persons who are given a clear rubric to follow. There are some instances in the spreadsheets where clear errors in the logging of exit and/or enter times are found. Also, some data points are missing cells such as exit lane usage, and contain unknown gender cells (up to 5% of data in Building 5 is unknown gender). This only adds to the errors and uncertainty that is already inherent in human behavior field studies, so mistakes in the logging of the spreadsheet data from the raw video footage should be avoided at all costs.

Spreadsheets could also state whether certain occupants experienced a queue at each camera view. Although sections of queuing were determined based on the density filter and camera/off-camera times a cell stating the occurrence of a queue would save analysis time. The methods used to determine queuing in the data still contain false positives and true negatives, so a queue cell in the spreadsheets would minimize statistical uncertainty.

Questionnaire surveys are very powerful tools, especially concerning human behavior data. Surveys should be given to every drill participant after the evacuation to collect additional data that cannot be shown using just the spreadsheet data. Questionnaire surveys can aid in collecting data on social platooning, as well as passing and merging scenarios that are not captured on the video cameras.

6.5.2 Future Research

Additional research on the calculation of density is needed to better define this seemingly abstract concept. What happens to speed vs. density R^2 values when density is calculated differently? Why are R^2 values for different stairwells significantly different when the same density calculation is used? Is one method of calculating density significantly better than others? The specific density calculation methods employed should be a primary focus in future density studies. Few reports in the fire protection literature explicitly define density and present the methods used to calculate it. Future studies on density and its impact on egress must do this to aid in obtaining the most effective way to define and calculate this important egress parameter.

Because there is not a plethora of human behavior research and its impact on evacuation and people movement, future evacuation studies should focus on human behavior aspects such as platoon movement, passing behavior, and merging behavior. Although this study analyzed platoon movement with respect to passing behavior, the potential effects that merging has on platoons are not covered. Future research should aim to analyze how these three phenomena interact and how the dynamics of the platoon changes during passing and merging situations.

Because a platoon analysis is only done over two floors in two different stairs, more analyses must be done to determine whether the results are unique to these sections of stairs, or whether the platoon movement patterns are typical in high-rise stairwell evacuations. An examination of platoon dynamics during the entire descent is an area of research that would benefit the fire protection community, as well. How do platoons change during the course of a high-rise descent? What are the effects involved with platoons that grow or decrease in size? Do merging individuals add to the size of a stair platoon, or do they typically split a stair platoon? These questions must be addressed in future studies on platoon movement.

Platoons and mergers are defined specifically in Chapter 4, but how do the results change with differing definitions? Platoon research, especially, is a relatively new concept in the fire protection egress field, so additional studies on how to define and identify platoons are needed. Rather than identifying platoons based on the movement within the stair, platoons can be identified based on social groups, which is very much related to pre-evacuation studies. Platoon research that focuses on social interactions within the workplace, or friend and family interactions in apartment/hotel settings can be coupled with pre-evacuation studies to examine the effects that one area has on the other.

The majority of the analyses conducted in this study focused on sections of the stairwell where there are no queues. Queuing within stairs has been shown to be quite common during total high-rise evacuations [5, 17, 28, 31]. Because of the limitations of the data and the unpredictable results that stems from flow stagnation, analyses that involved descent times (thus, local movement speeds) within this study involved no queues. Future research could investigate ways to analyze sections of stairs where there are queues to obtain accurate egress results. Studies on the impacts that queues have on platoon dynamics, or passing and merging behavior would be beneficial to the egress research community.

Appendix A: MATLAB Codes

See Section 4.2 for a detailed explanation of the code and the calculation of density.

1. Number of People in Camera View when Occupant Enters

```matlab
A=Data;
P=195;
A(isnan(A))=0;
enter=A(:,1)
exit=A(:,2)
for i = (1:P)
    for j = (1:P)
        if enter(j)<=enter(i)&&enter(i)<=exit(j)
            output(i,j)=1;
        else output(i,j)=0;
        end
        if enter(j)==0
            output(i,j)=0;
        end
    end
end

result=sum(output,2)
```

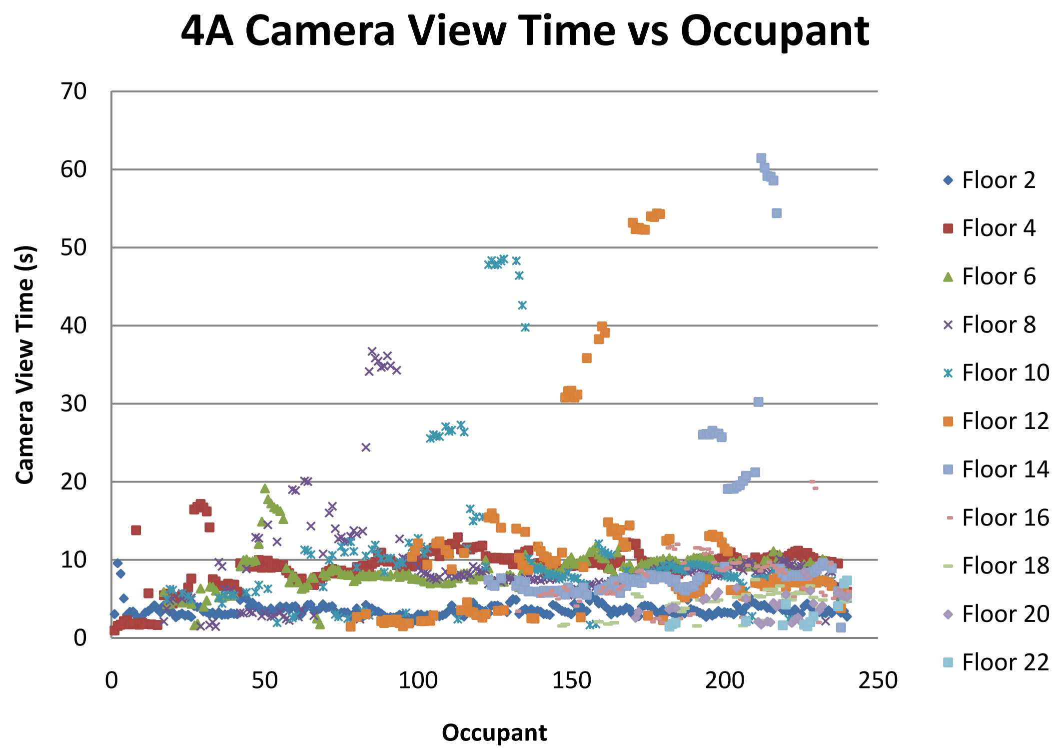
2. Number of People in Camera View when Occupant Exits

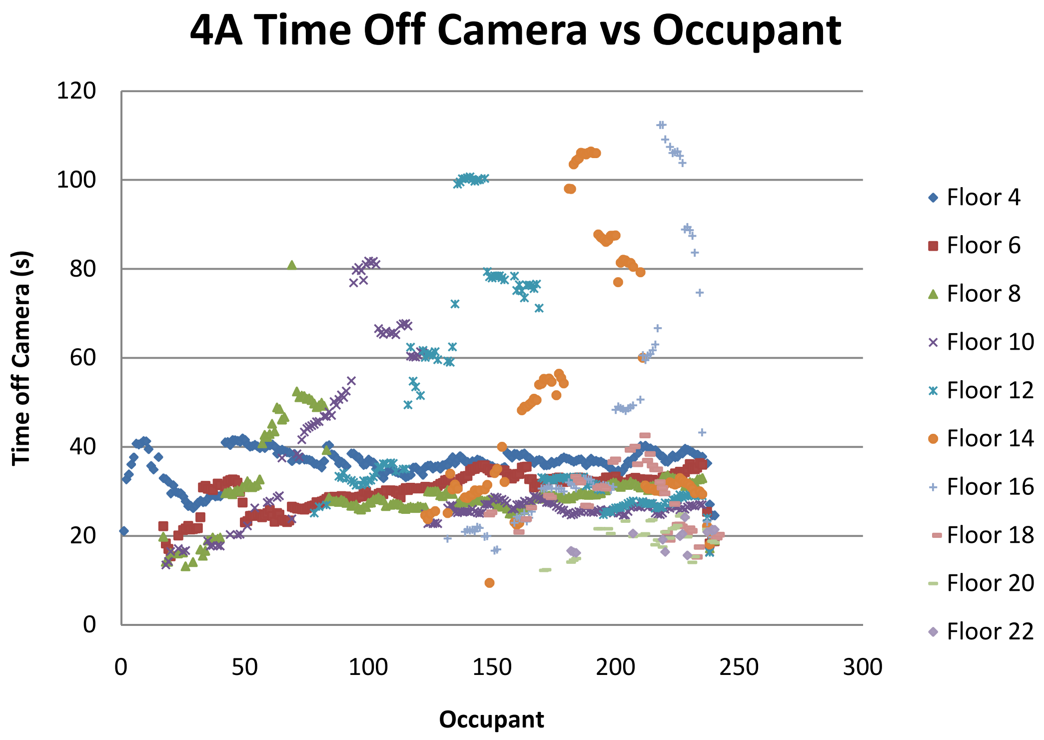
```matlab
A=Data;
P=195;
A(isnan(A))=0;
enter=A(:,1)
exit=A(:,2)
for i= (1:P)
    for j= (1:P)
        if enter(j)<=exit(i)&&exit(i)<=exit(j)
            output(i,j)=1;
        else output(i,j)=0;
        end
        if enter(j)==0
            output(i,j)=0;
        end
    end
end

result=sum(output,2)
```

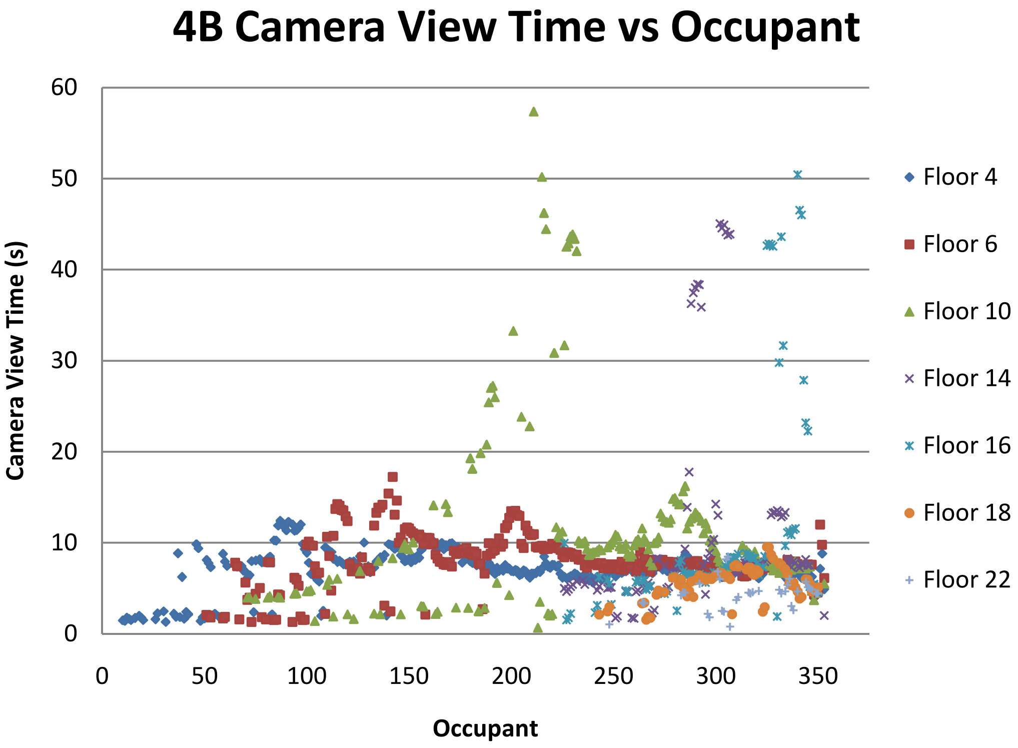
Appendix B: Camera and Off Camera Times

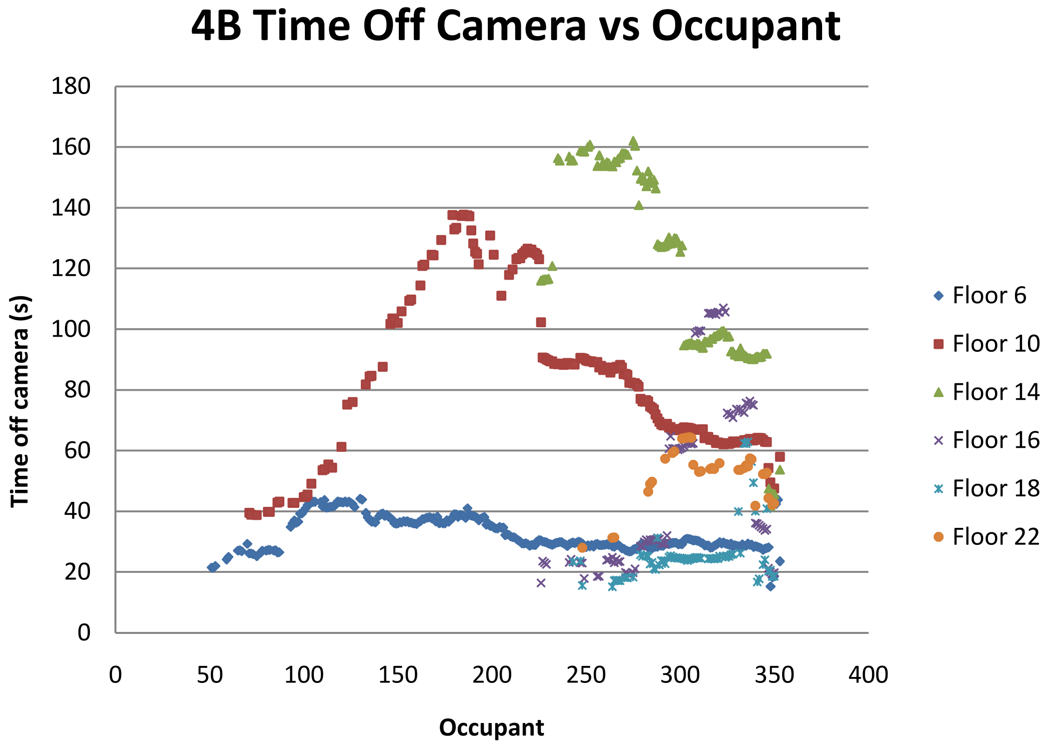
Stair 4A



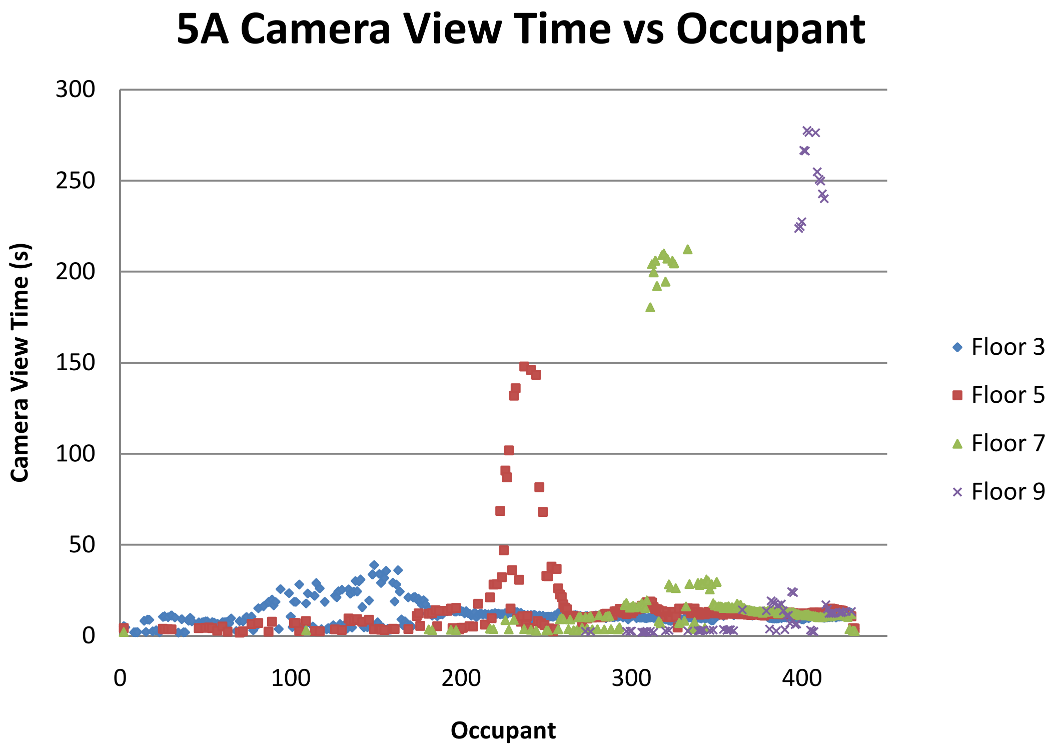


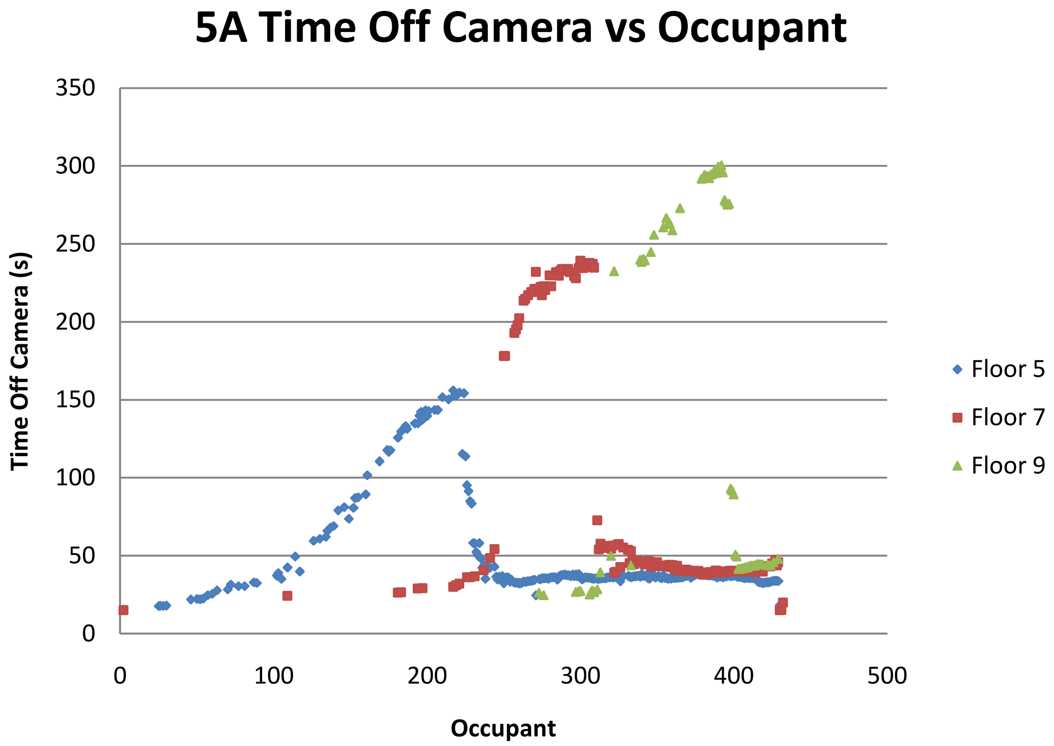
Stair 4B


4B Camera View Time vs Occupant
Camera View Time (s)
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
Occupant
Floor 4
Floor 6
Floor 10
Floor 14
Floor 16
Floor 18
Floor 22

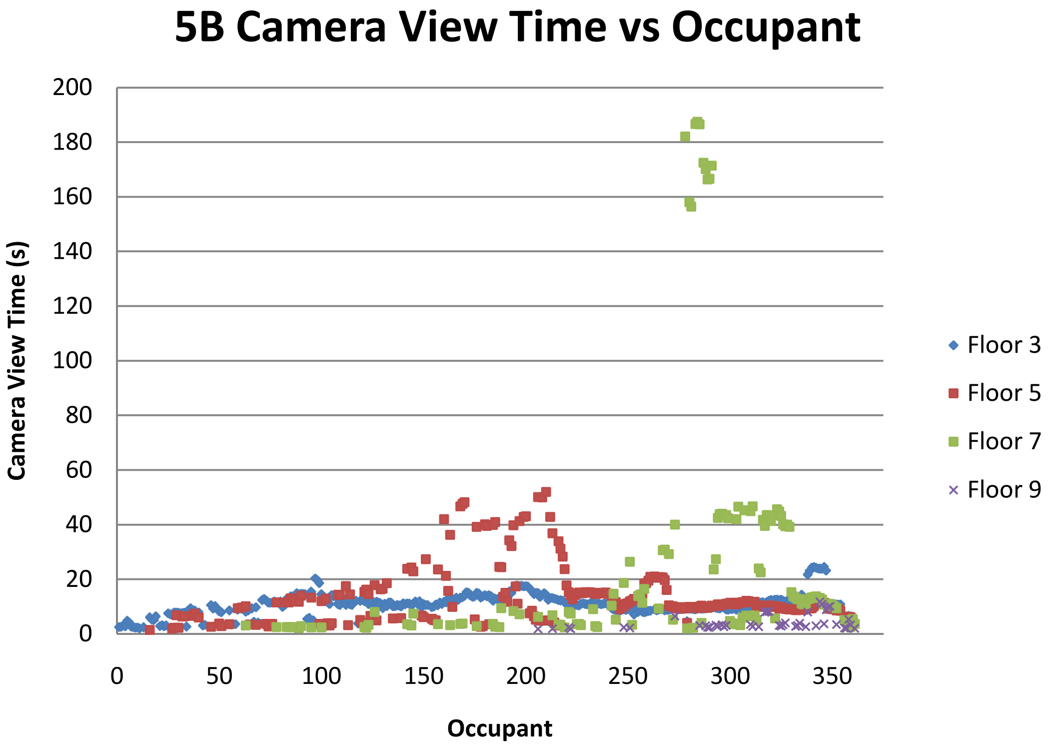

4B Time Off Camera vs Occupant
Time off camera (s)
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
400
Occupant
Floor 6
Floor 10
Floor 14
Floor 16
Floor 18
Floor 22

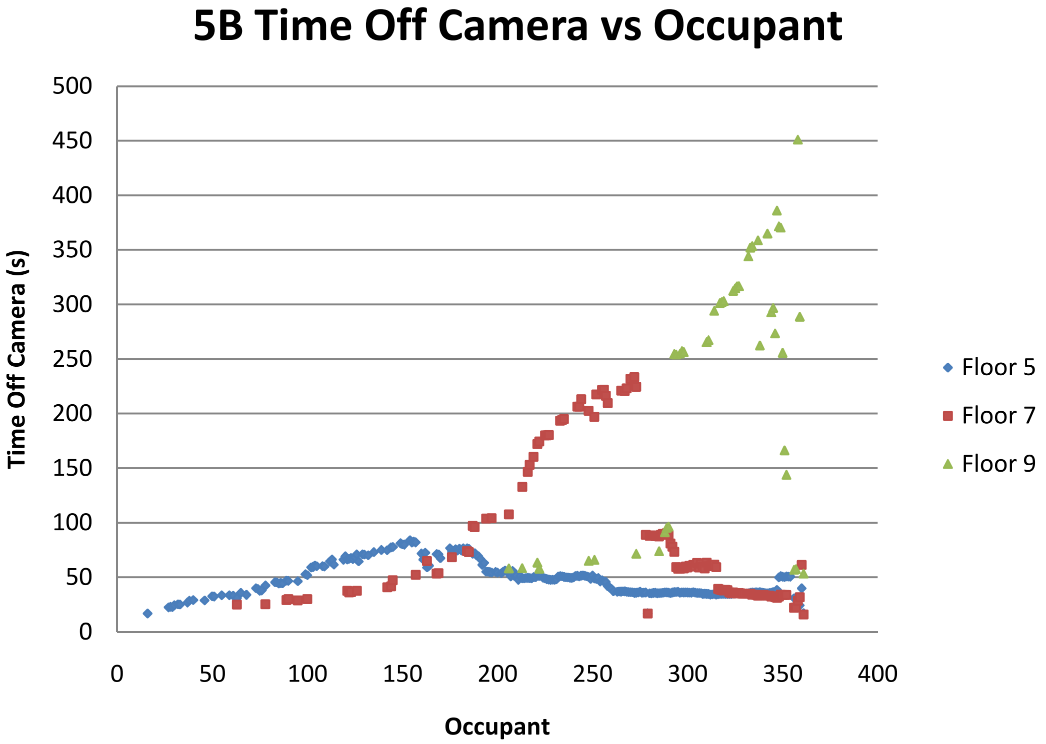
Stair 5A


5A Camera View Time vs Occupant
Camera View Time (s)
300
250
200
150
100
50
0
0
100
200
300
400
Occupant
Floor 3
Floor 5
Floor 7
Floor 9

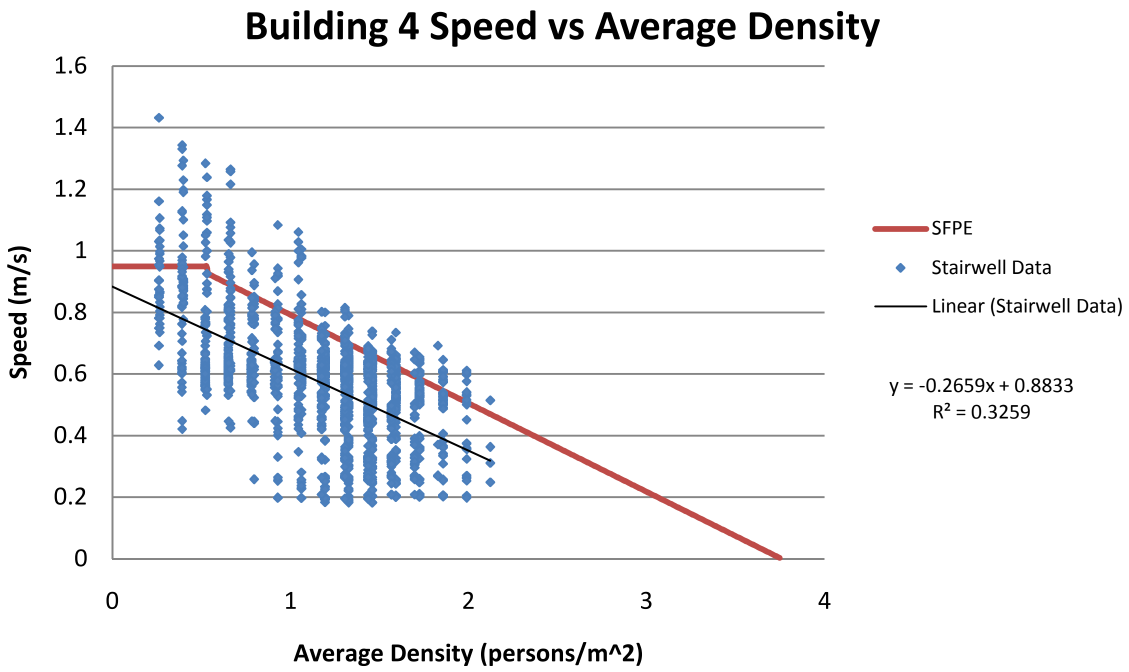

5A Time Off Camera vs Occupant
Time Off Camera (s)
350
300
250
200
150
100
50
0
0
100
200
300
400
500
Occupant
Floor 5
Floor 7
Floor 9

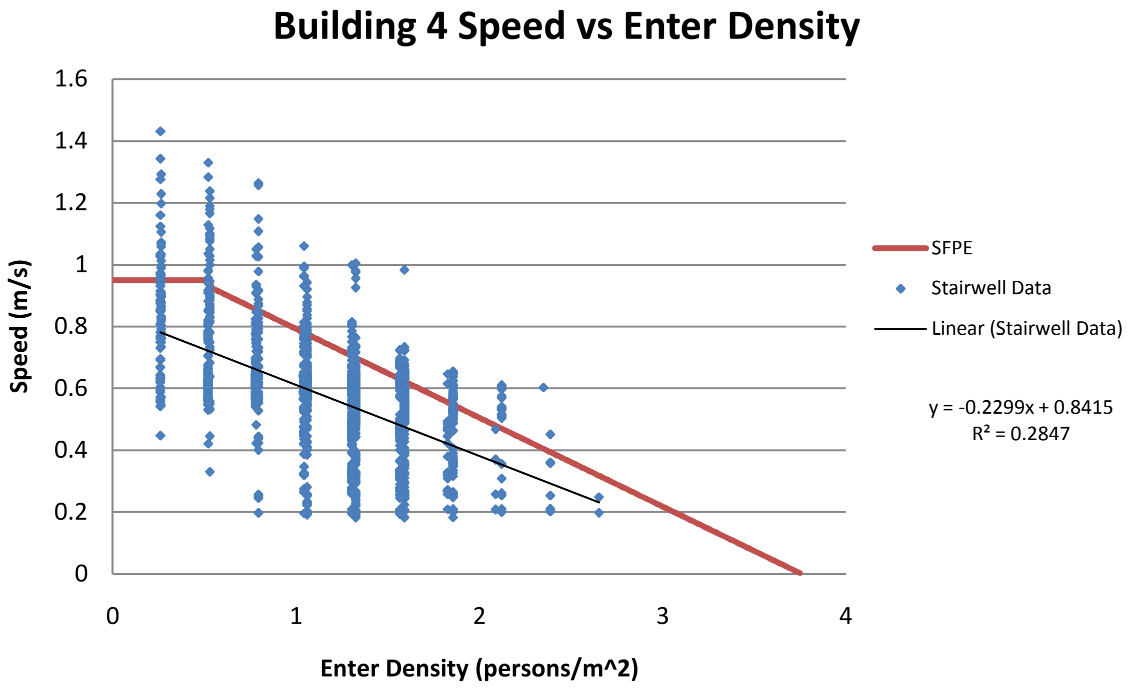
Stair 5B

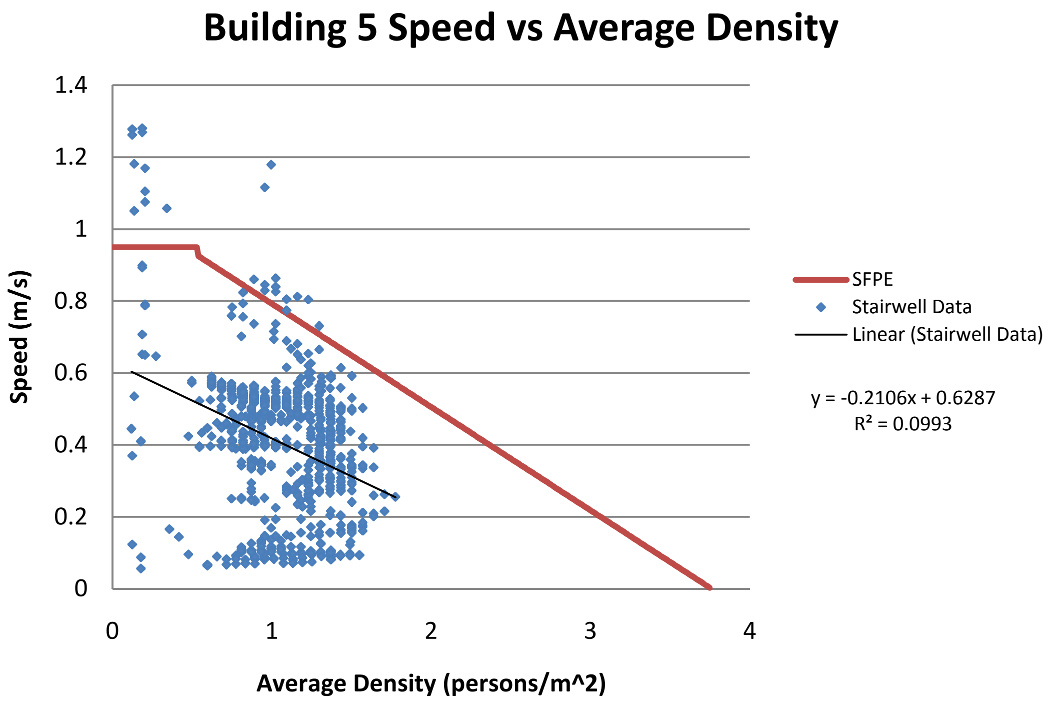

5B Camera View Time vs Occupant
Camera View Time (s)
200
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
Occupant
◆ Floor 3
■ Floor 5
■ Floor 7
× Floor 9

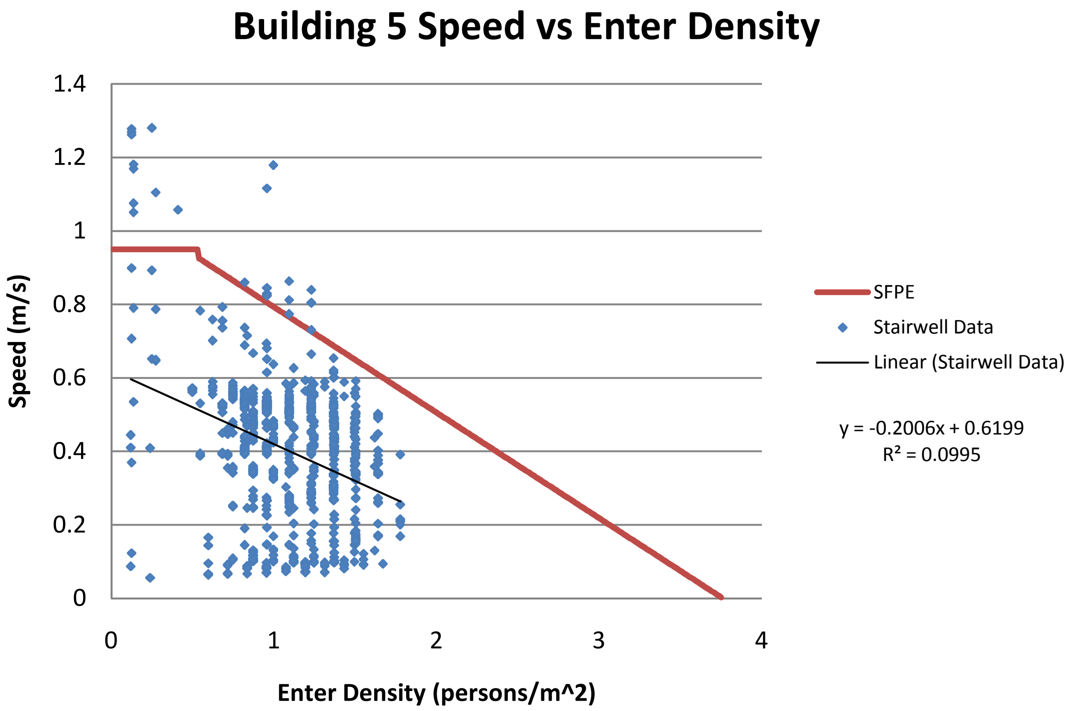

5B Time Off Camera vs Occupant
Time Off Camera (s)
500
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
Occupant
◆ Floor 5
■ Floor 7
▲ Floor 9

Appendix C: Speed vs. Density Graphs

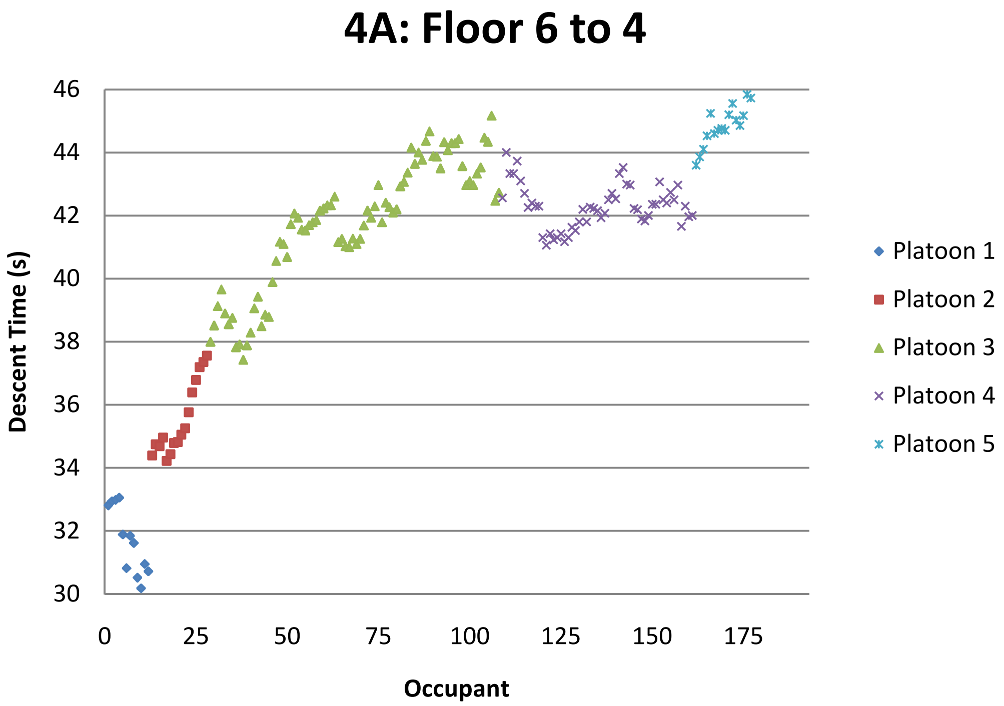


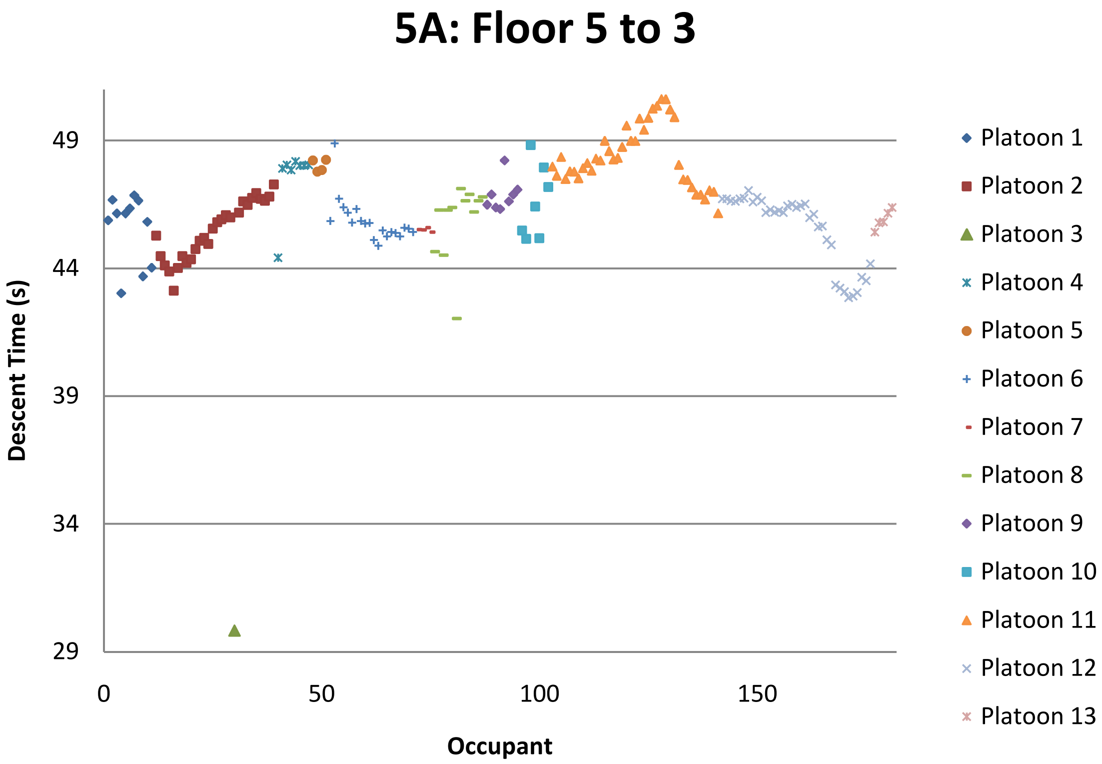



Building 5 Speed vs Average Density
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
Speed (m/s)
Average Density (persons/m^2)
SFPE
Stairwell Data
Linear (Stairwell Data)
y = -0.2106x + 0.6287
R² = 0.0993


Building 5 Speed vs Enter Density
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
Speed (m/s)
Enter Density (persons/m^2)
SFPE
Stairwell Data
Linear (Stairwell Data)
y = -0.2006x + 0.6199
R² = 0.0995

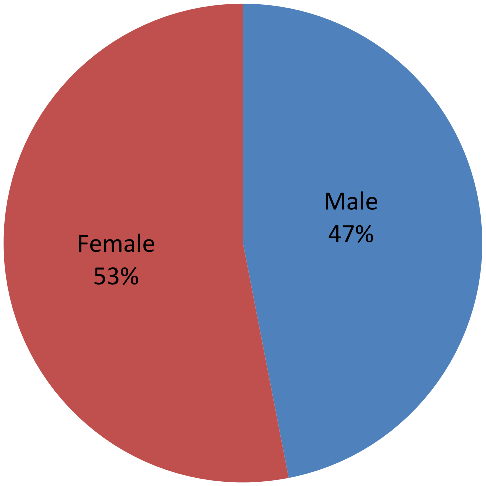
Appendix D: Descent Time Plots of Platoons with No Merging

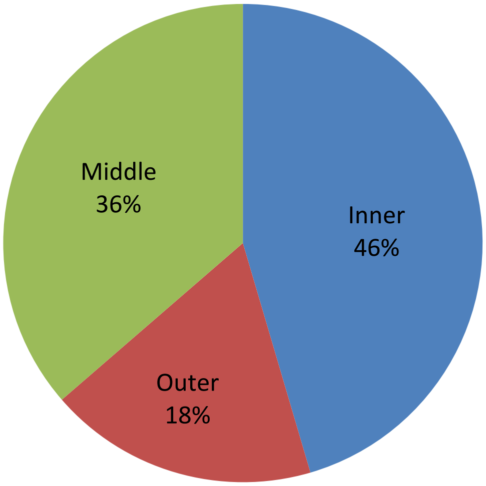




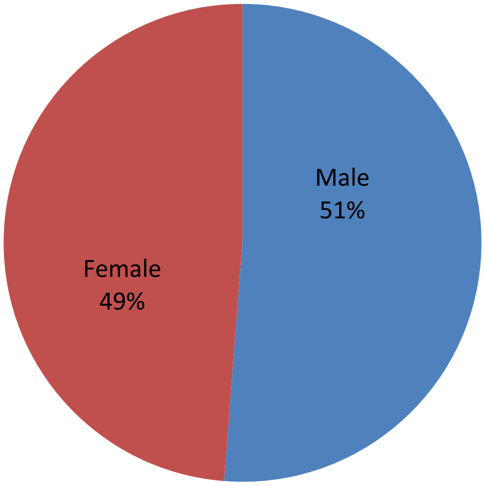
Appendix E: Passing Behavior Demographic Pie Charts

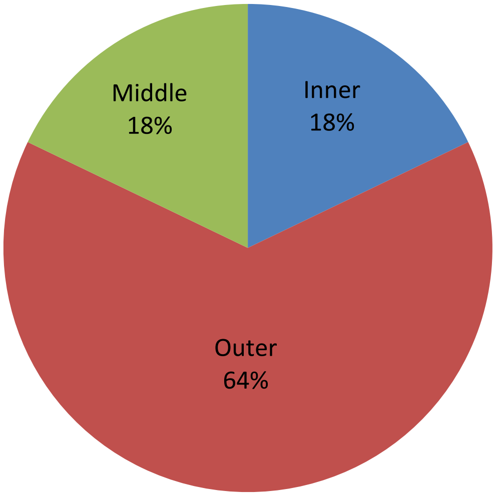
Building 4 Single-Person Passers



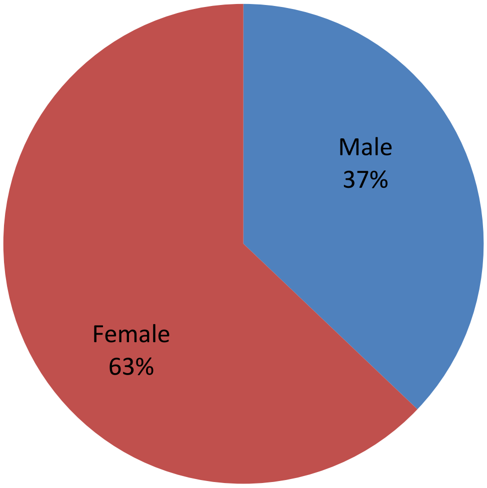


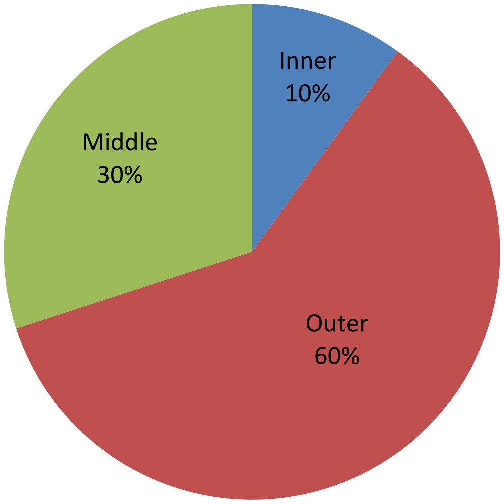
Building 4 Those Passed by a Single Person



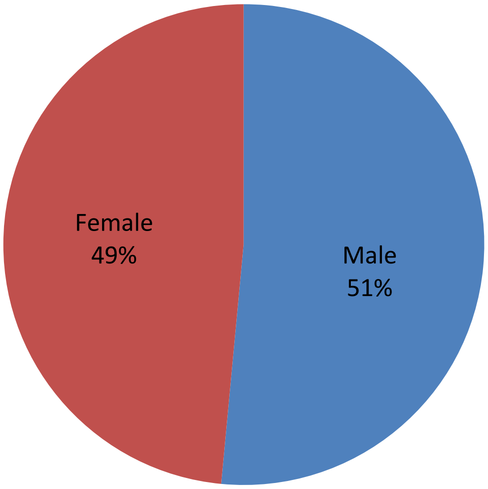


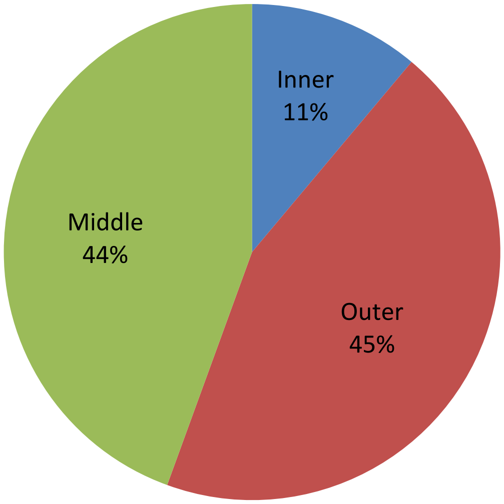
Building 4 Multi-Person Passers



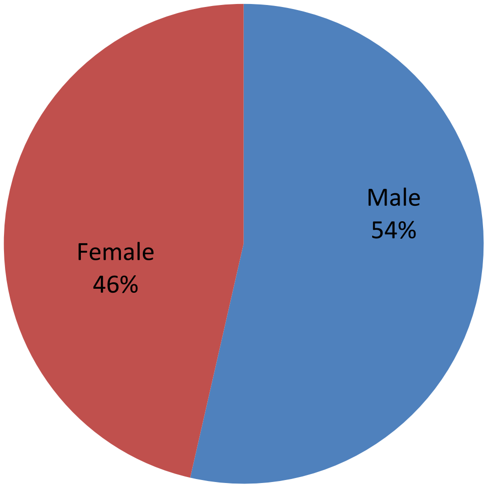


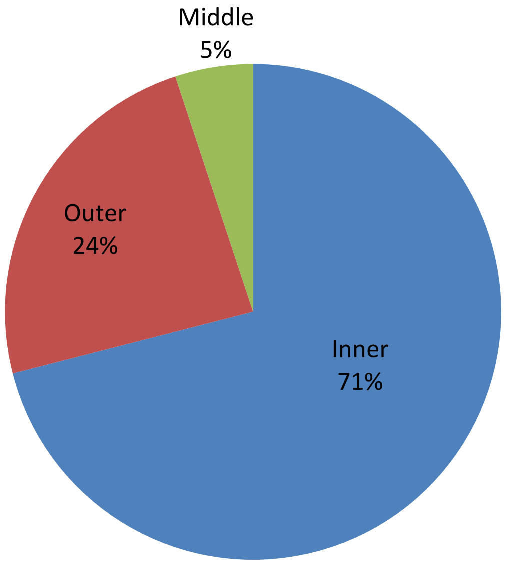
Building 4 Those Passed by Multiple People



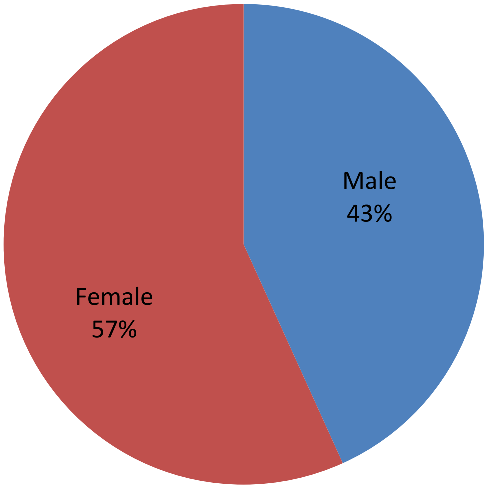


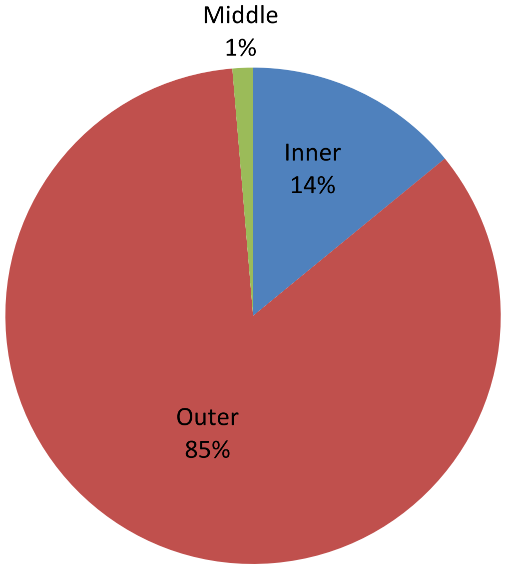
Building 5 Single-Person Passers



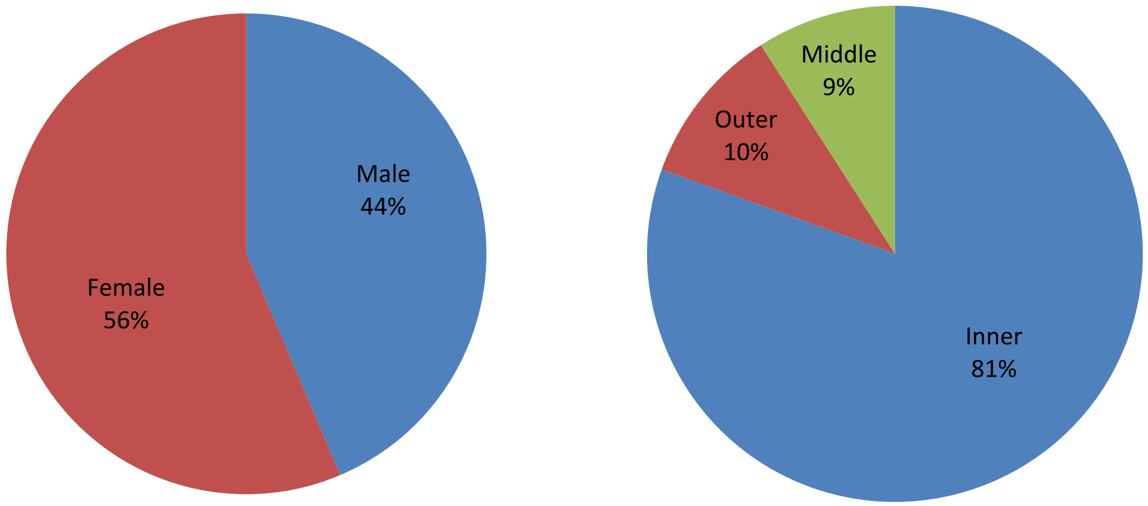


Building 5 Those Passed by a Single Person

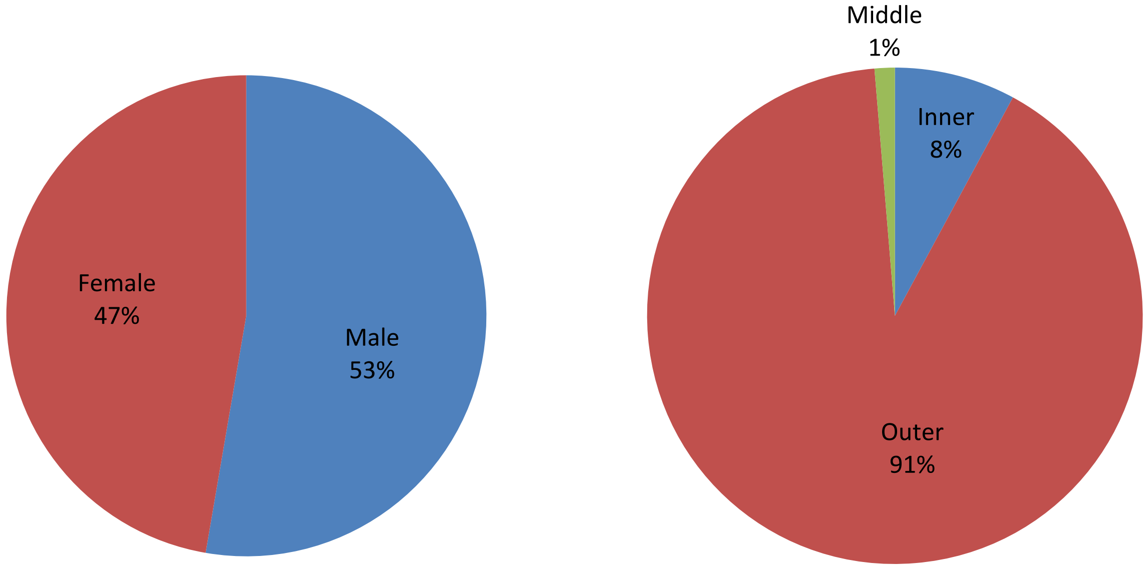




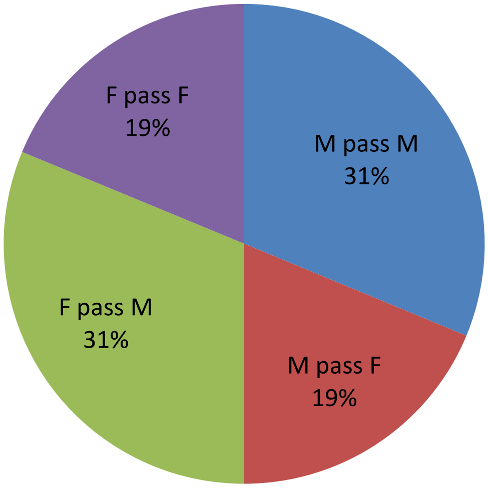
Building 5 Multi-Person Passers

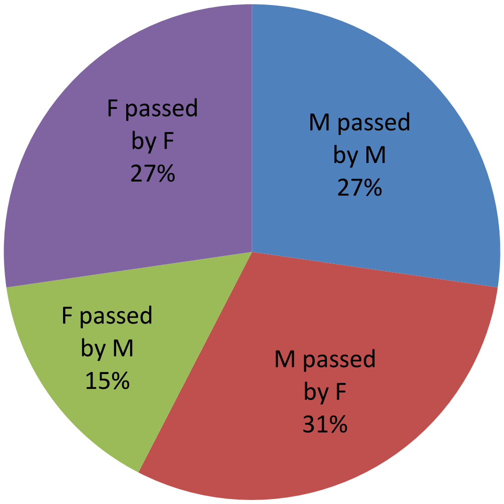


Building 5 Those Passed by Multiple People

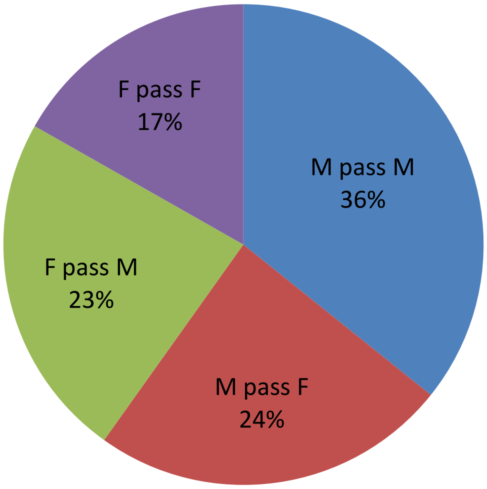


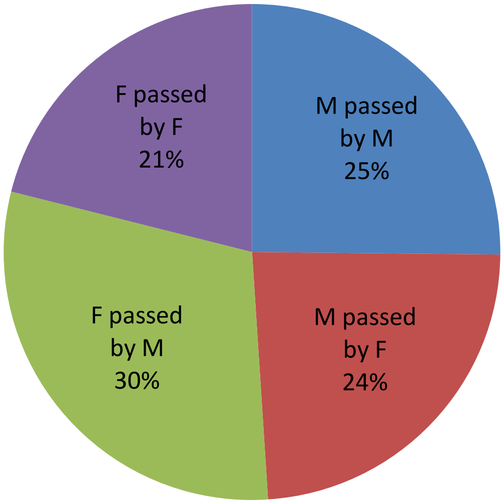
Building 4 Single-Person Passing Scenarios



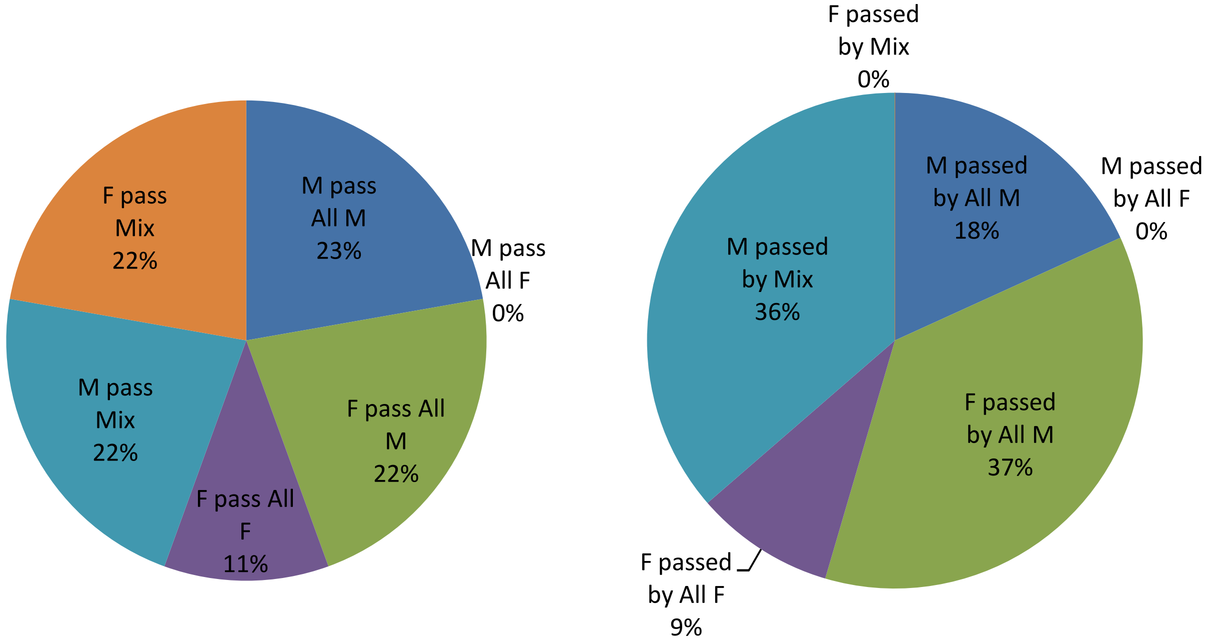


Building 5 Single-Person Passing Scenarios

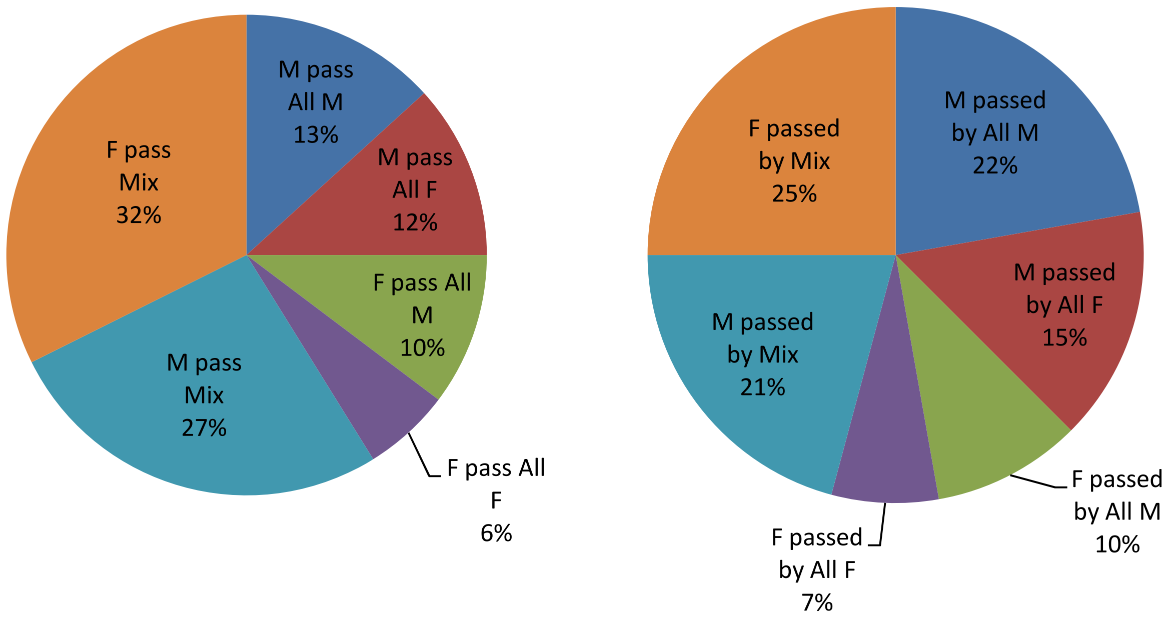




Building 4 Multi-Person Passing Scenarios



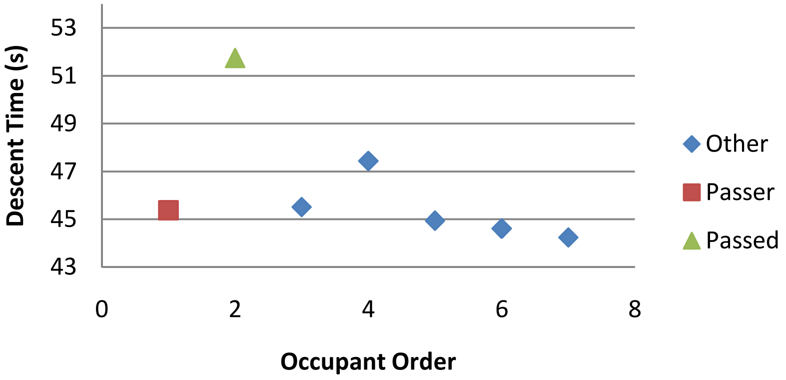
Building 5 Multi-Person Passing Scenarios

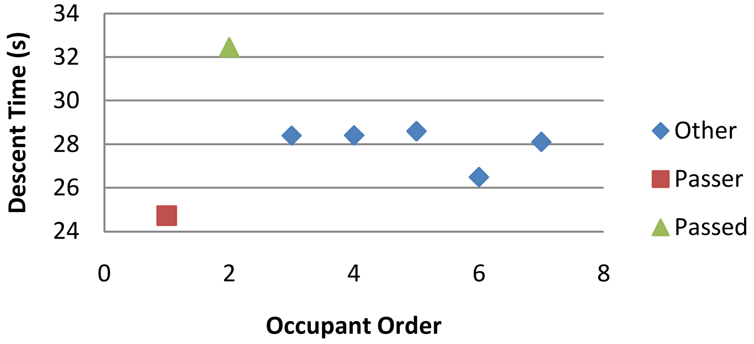


Appendix F: Descent Times of Passing Events

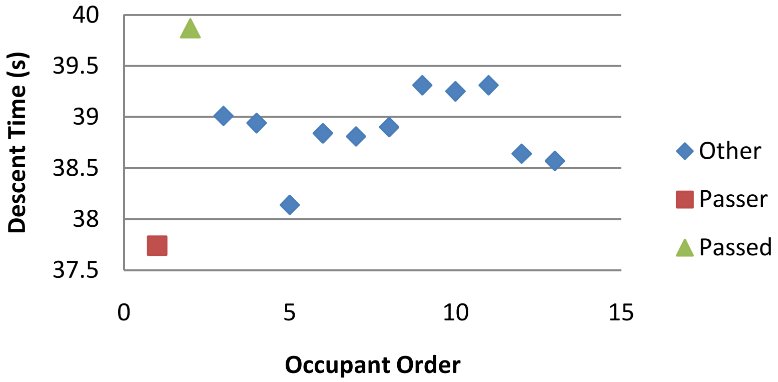
Stair 4A

Floor 18 to 16

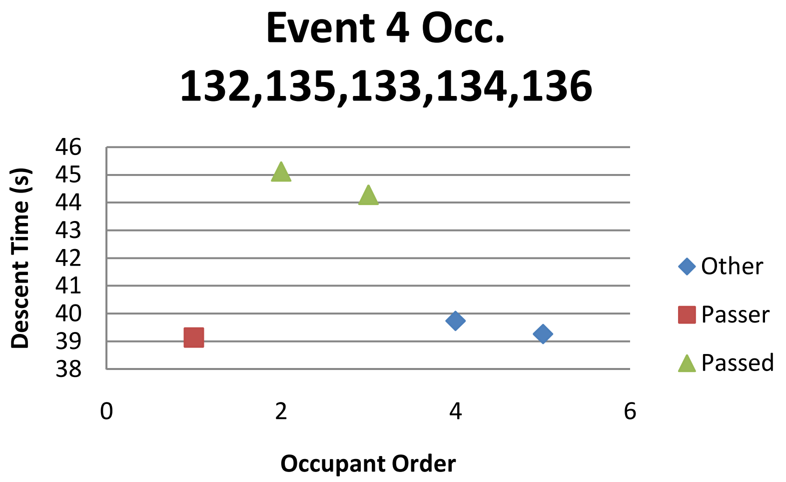

Event 1 Occ. 207,210-215


Event 2 Occ. 220,222-227

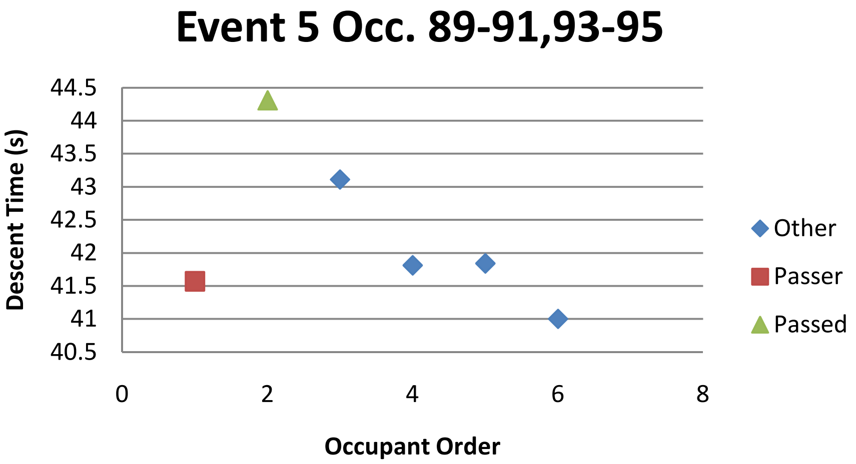
Floor 16 to 14

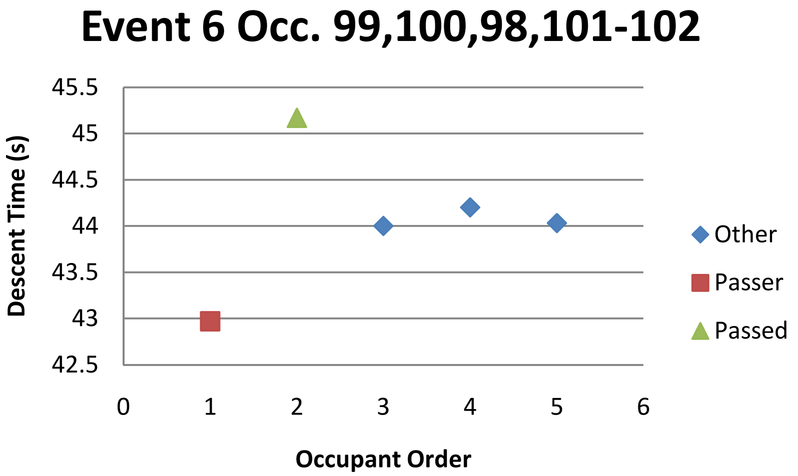

Event 3 Occ. 179,181-192

Floor 14 to 12



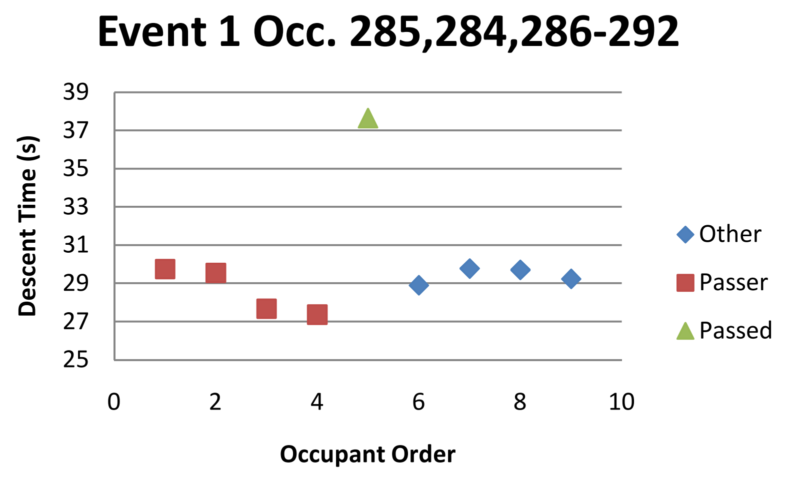
Floor 12 to 10



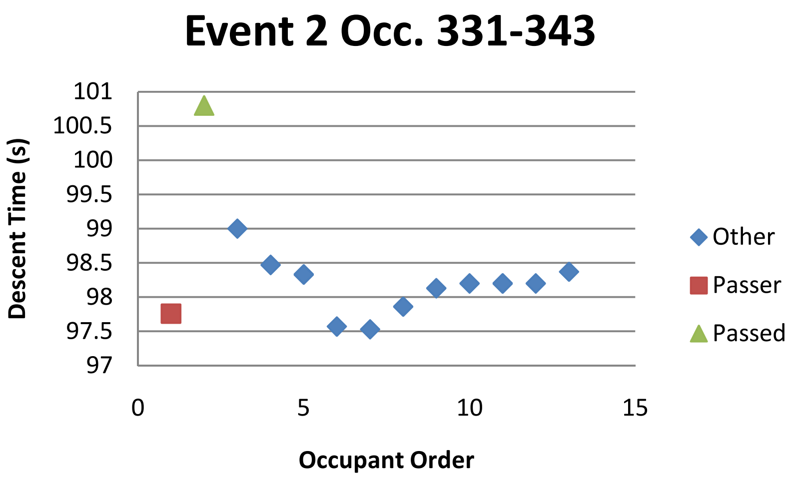


Stair 4B

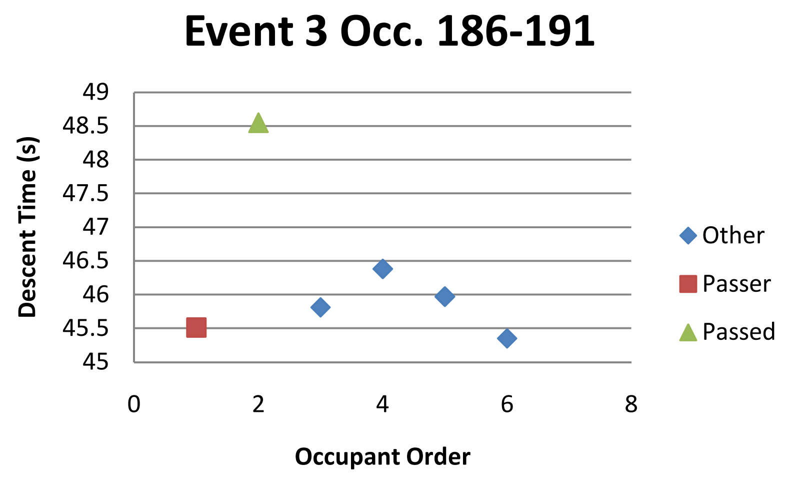
Floor 18 to 16



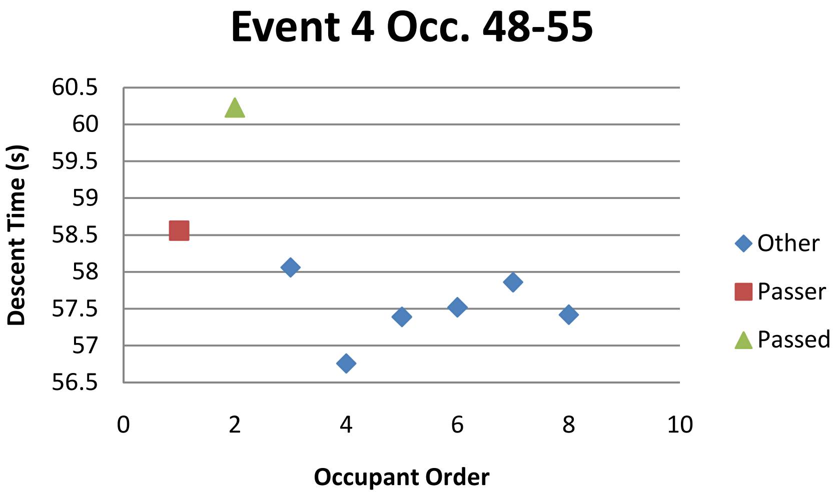
Floor 14 to 10

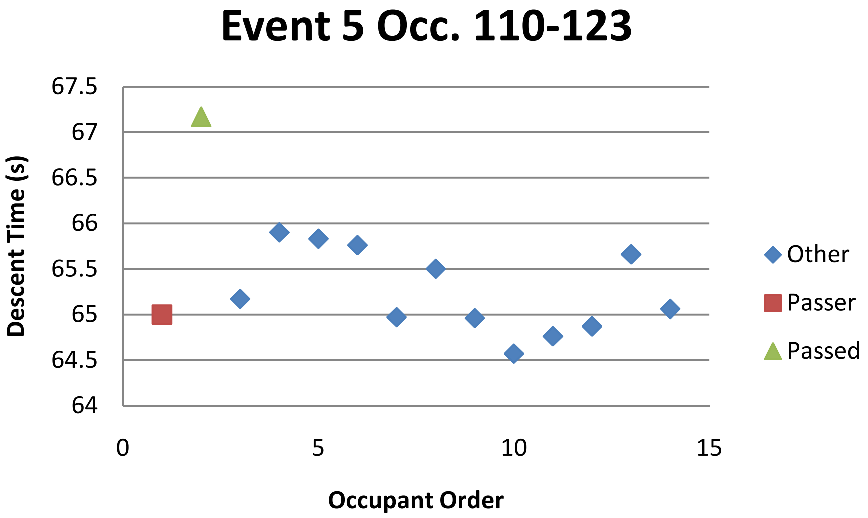


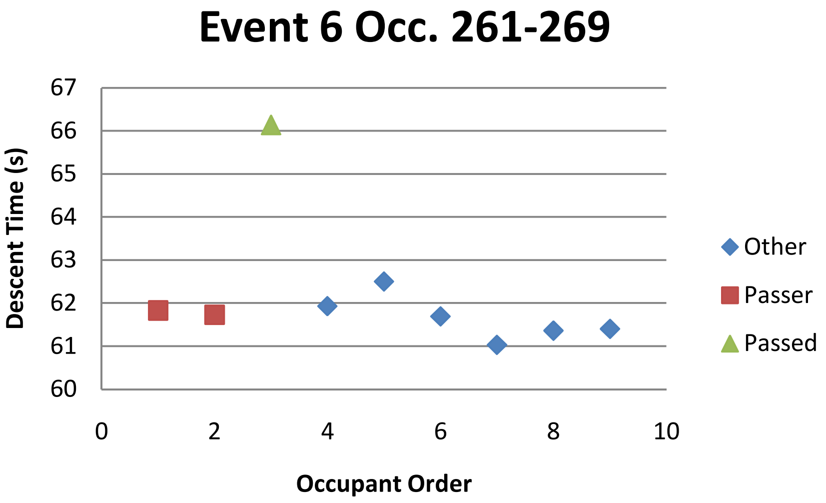
Floor 6 to 4



Floor 4 to P1


Event 4 Occ. 48-55
Descent Time (s)
60.5
60
59.5
59
58.5
58
57.5
57
56.5
0
2
4
6
8
10
Occupant Order
Other
Passer
Passed

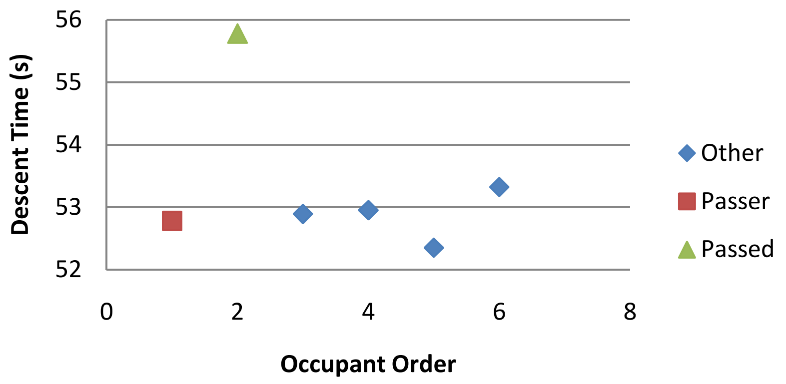

Event 5 Occ. 110-123
Descent Time (s)
67.5
67
66.5
66
65.5
65
64.5
64
0
5
10
15
Occupant Order
Other
Passer
Passed


Event 6 Occ. 261-269
Descent Time (s)
67
66
65
64
63
62
61
60
0
2
4
6
8
10
Occupant Order
Other
Passer
Passed

Stair 5A

Floor 7 to 5

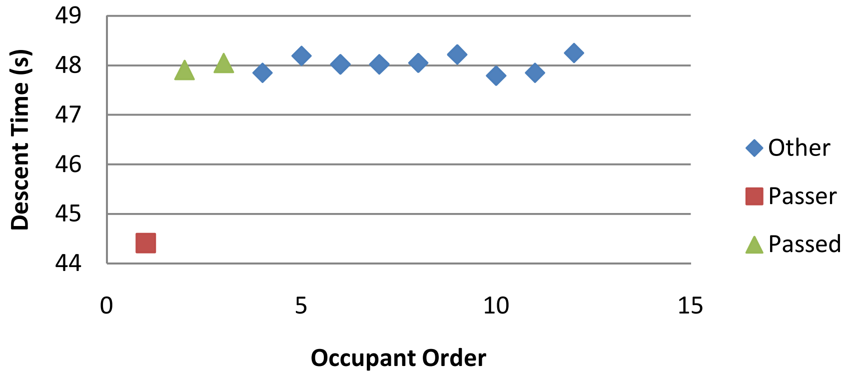
Event 1 Occ. 362-367

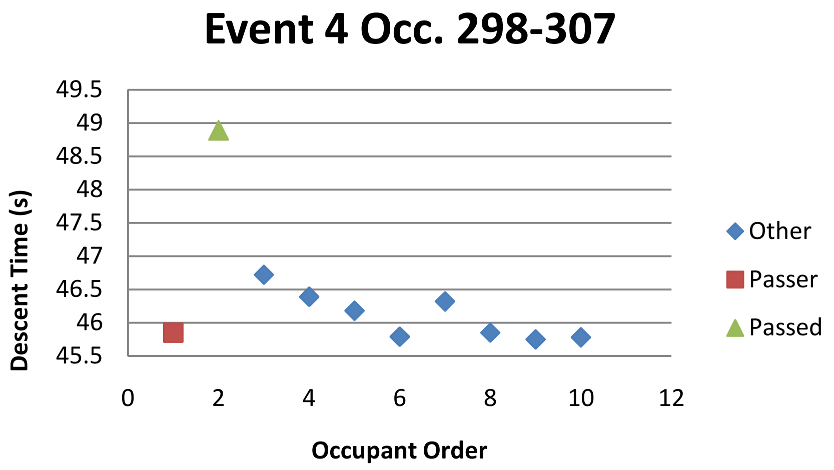


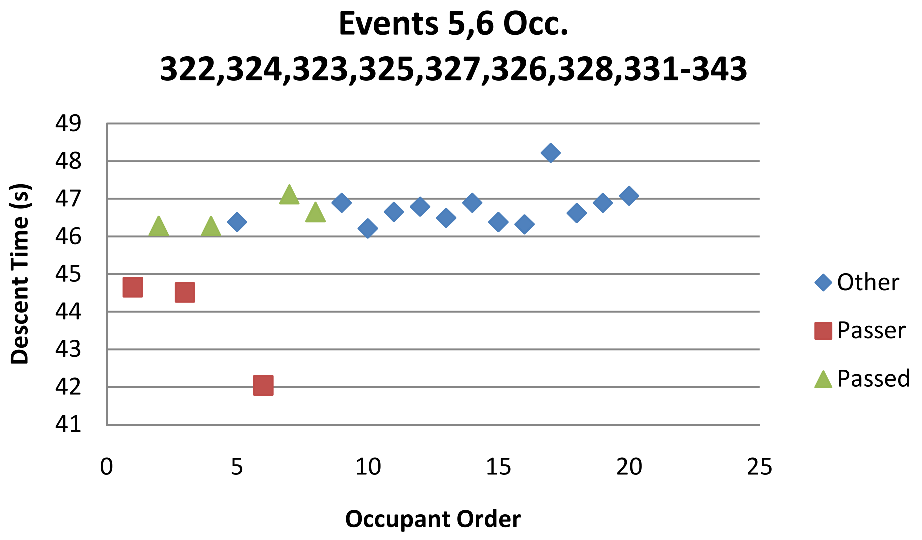
Event 2 Occ. 387-415

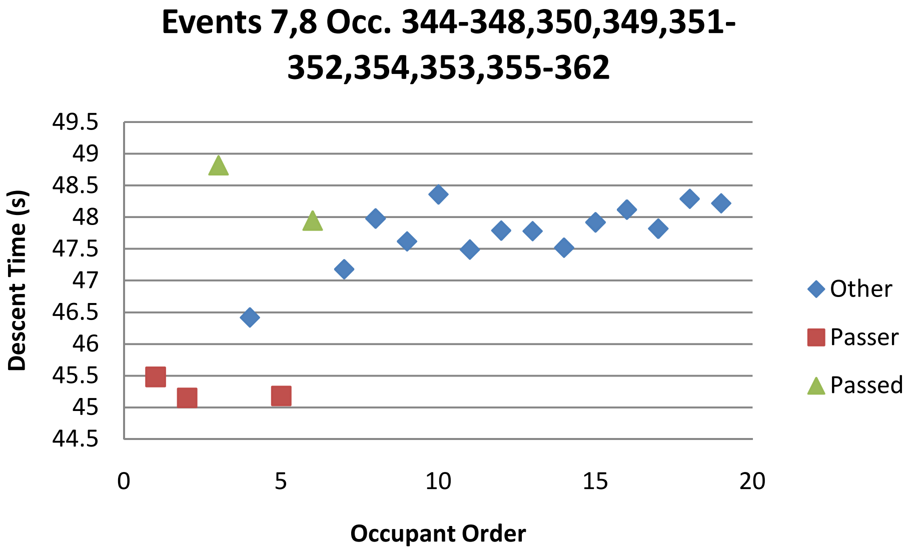
Floor 5 to 3

Event 3 Occ. 285,287-293,295,294,296-297

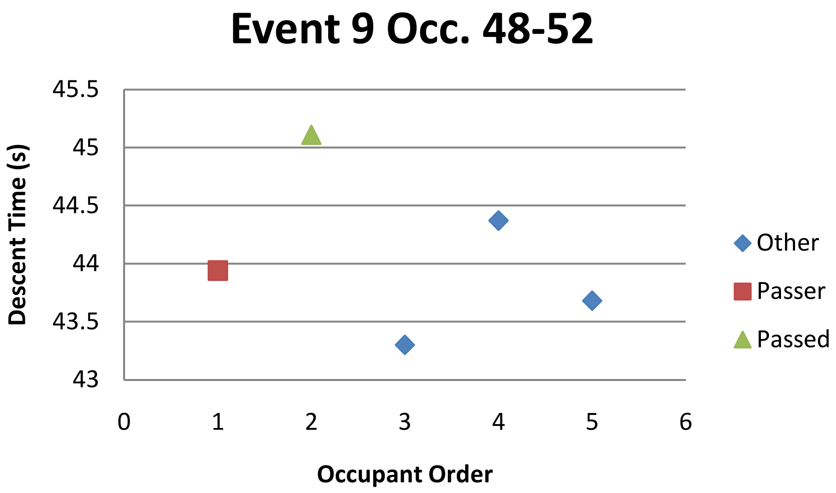


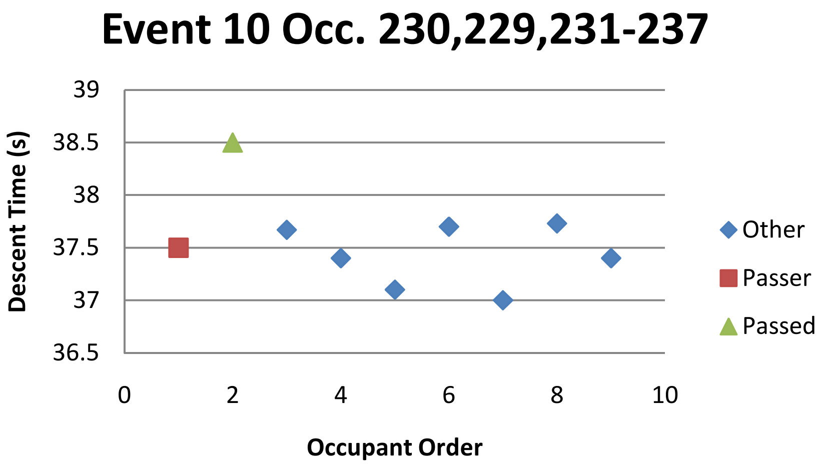

Event 4 Occ. 298-307
Descent Time (s)
49.5
49
48.5
48
47.5
47
46.5
46
45.5
0
2
4
6
8
10
12
Occupant Order
◆ Other
■ Passer
▲ Passed

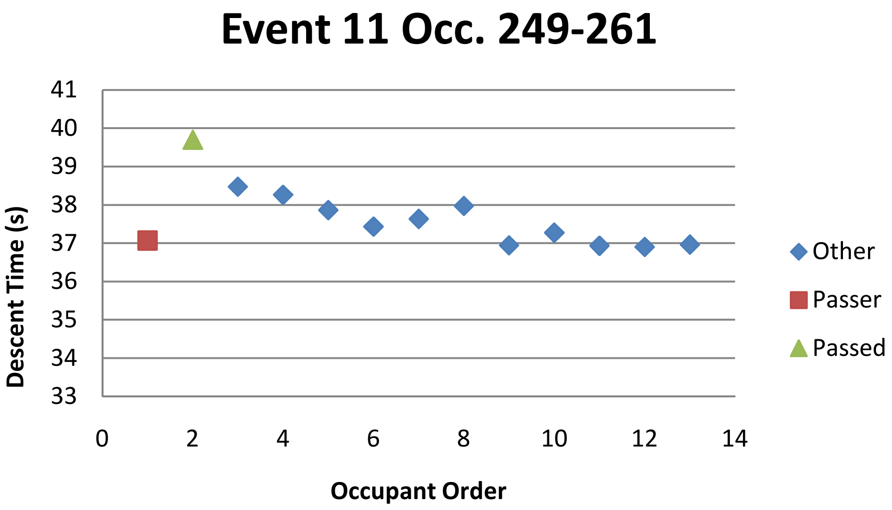

Events 5,6 Occ. 322,324,323,325,327,326,328,331-343
Descent Time (s)
49
48
47
46
45
44
43
42
41
0
5
10
15
20
25
Occupant Order
◆ Other
■ Passer
▲ Passed

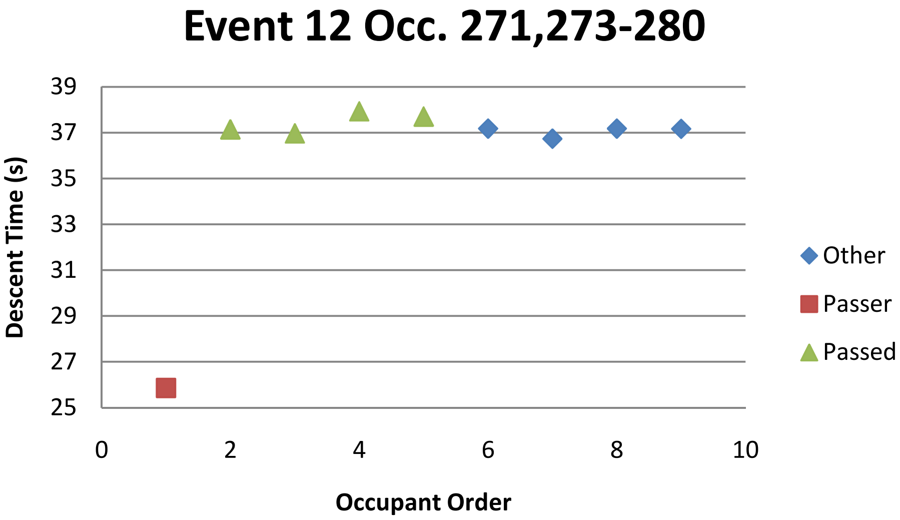

Events 7,8 Occ. 344-348,350,349,351-352,354,353,355-362
Descent Time (s)
49.5
49
48.5
48
47.5
47
46.5
46
45.5
45
44.5
0
5
10
15
20
Occupant Order
◆ Other
■ Passer
▲ Passed

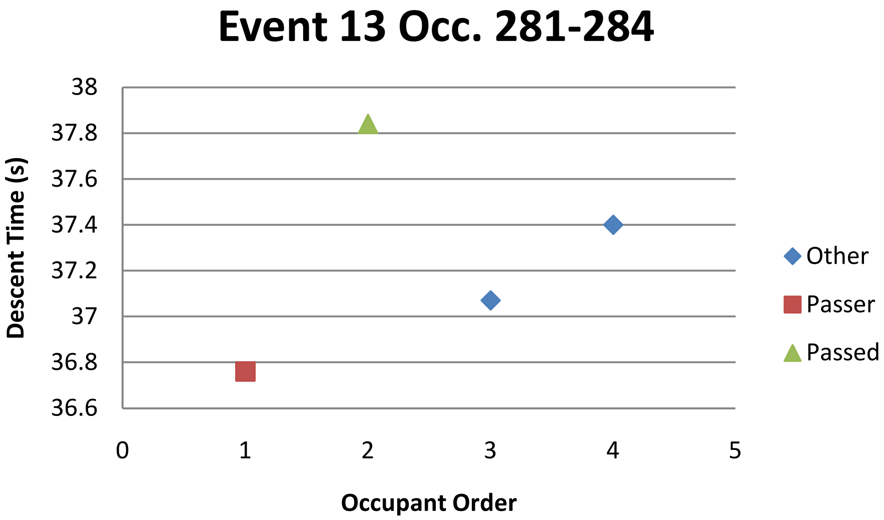
Floor 3 to 1

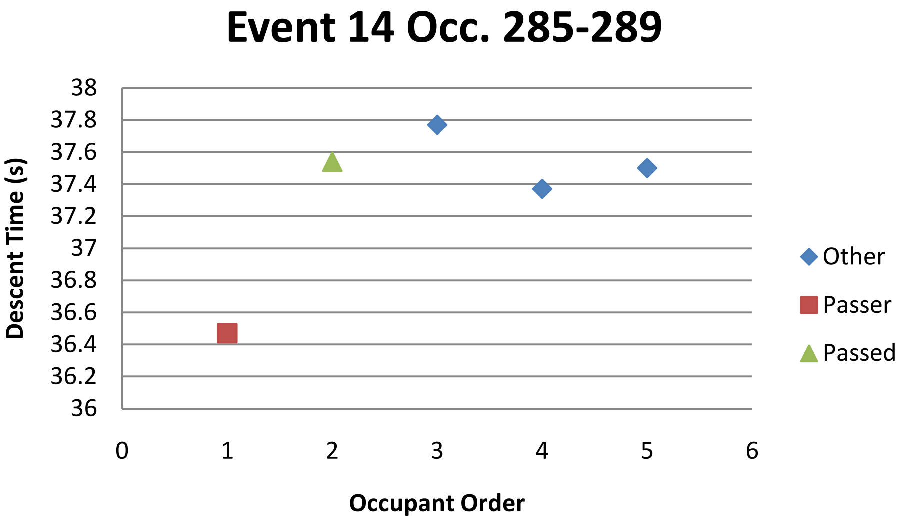

Event 9 Occ. 48-52
Descent Time (s)
45.5
45
44.5
44
43.5
43
0
1
2
3
4
5
6
Occupant Order
Other
Passer
Passed

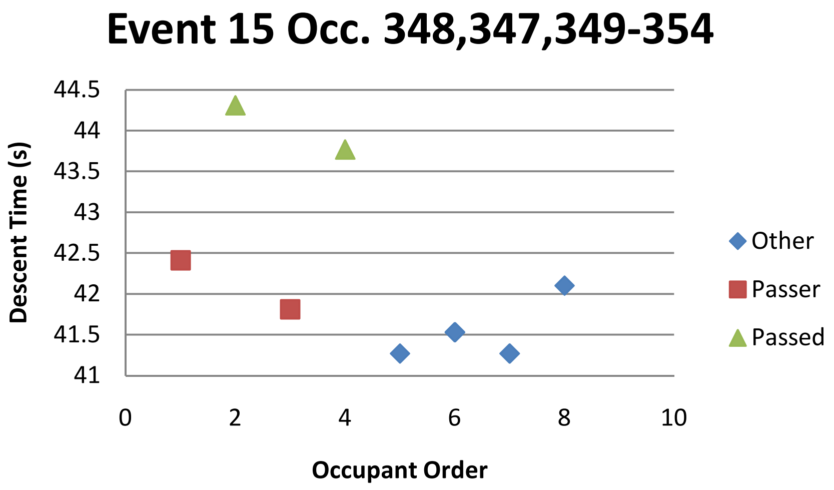

Event 10 Occ. 230,229,231-237
Descent Time (s)
39
38.5
38
37.5
37
36.5
0
2
4
6
8
10
Occupant Order
Other
Passer
Passed


Event 11 Occ. 249-261
Descent Time (s)
41
40
39
38
37
36
35
34
33
0
2
4
6
8
10
12
14
Occupant Order
Other
Passer
Passed


Event 12 Occ. 271,273-280
Descent Time (s)
39
37
35
33
31
29
27
25
0
2
4
6
8
10
Occupant Order
Other
Passer
Passed

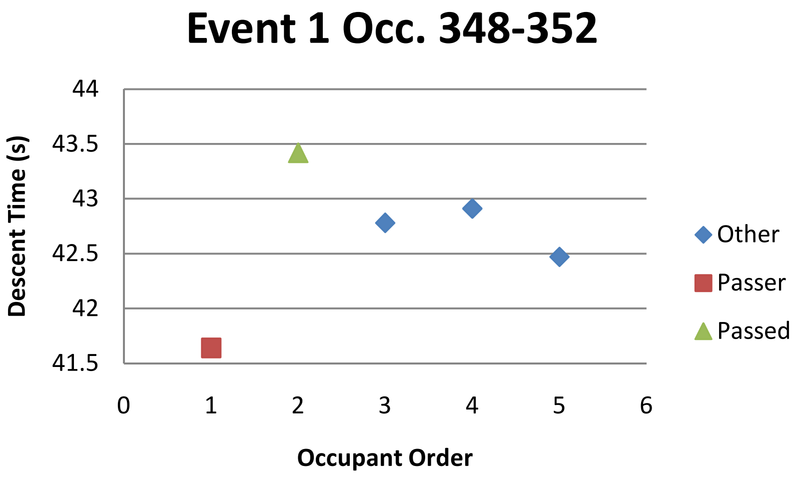

Event 13 Occ. 281-284
Descent Time (s)
38
37.8
37.6
37.4
37.2
37
36.8
36.6
0
1
2
3
4
5
Occupant Order
Other
Passer
Passed


Event 14 Occ. 285-289
Descent Time (s)
38
37.8
37.6
37.4
37.2
37
36.8
36.6
36.4
36.2
36
0
1
2
3
4
5
6
Occupant Order
Other
Passer
Passed

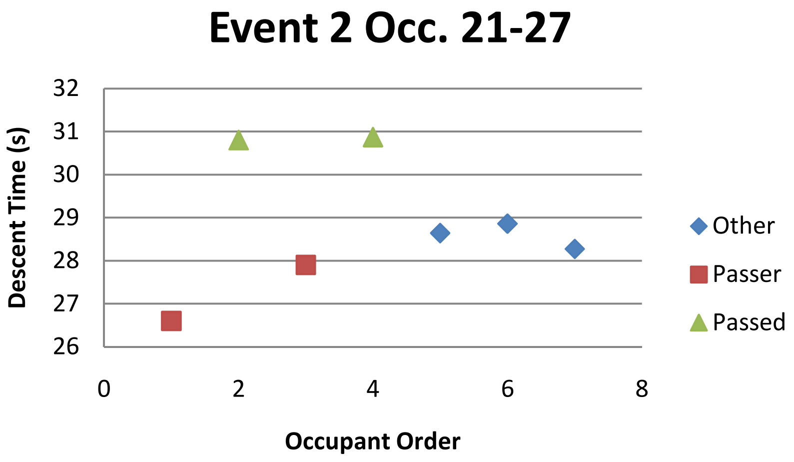


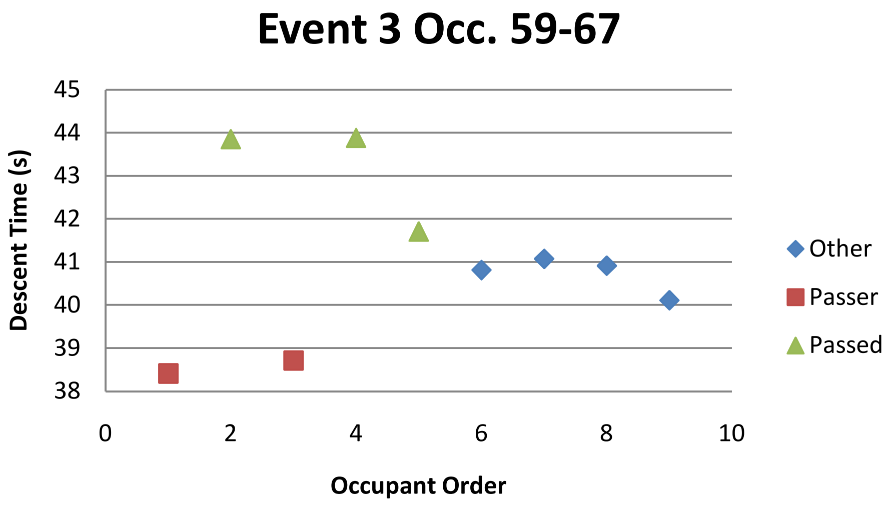
Stair 5B

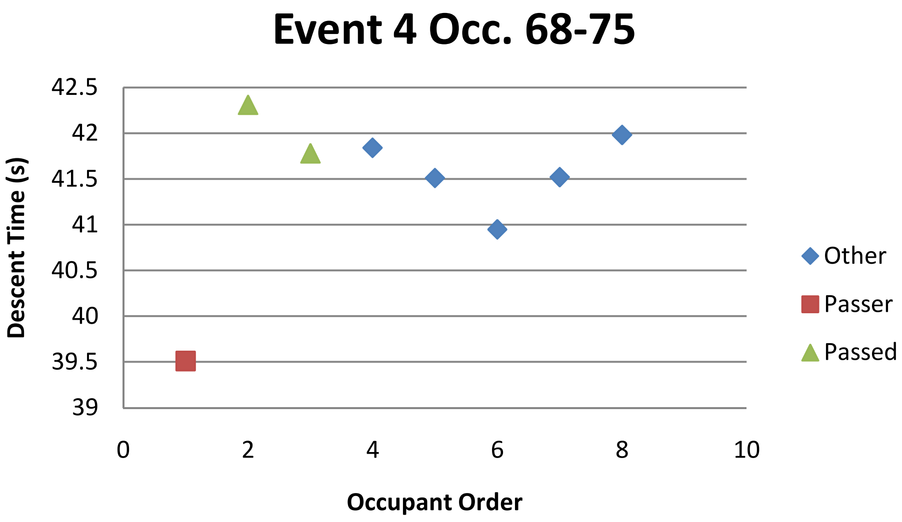
Floor 7 to 5

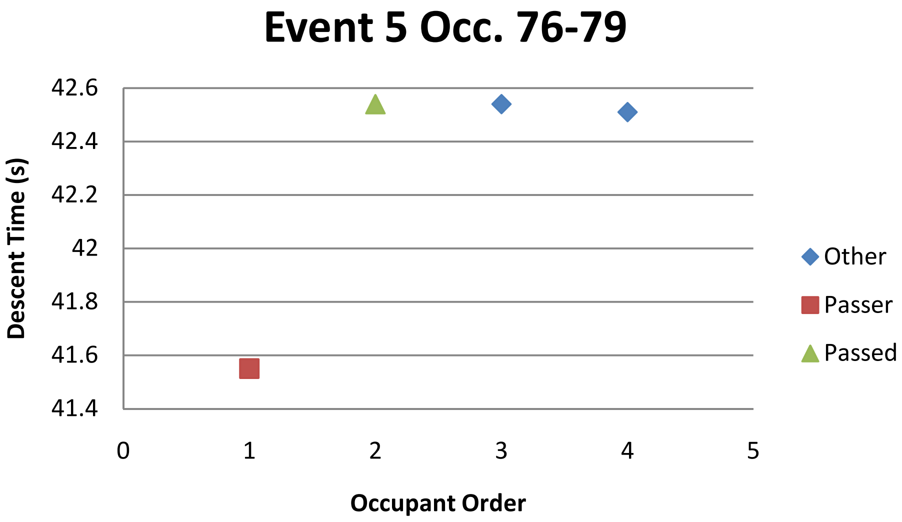


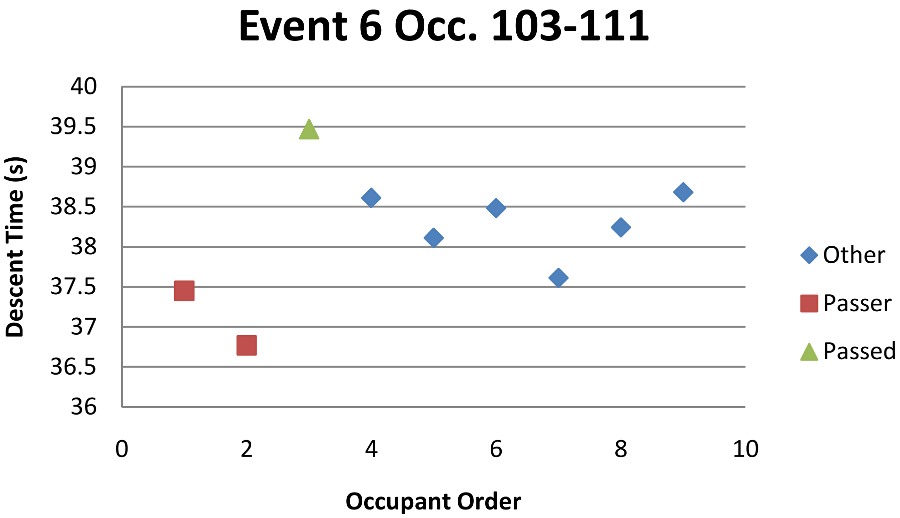
Floor 3 to 1

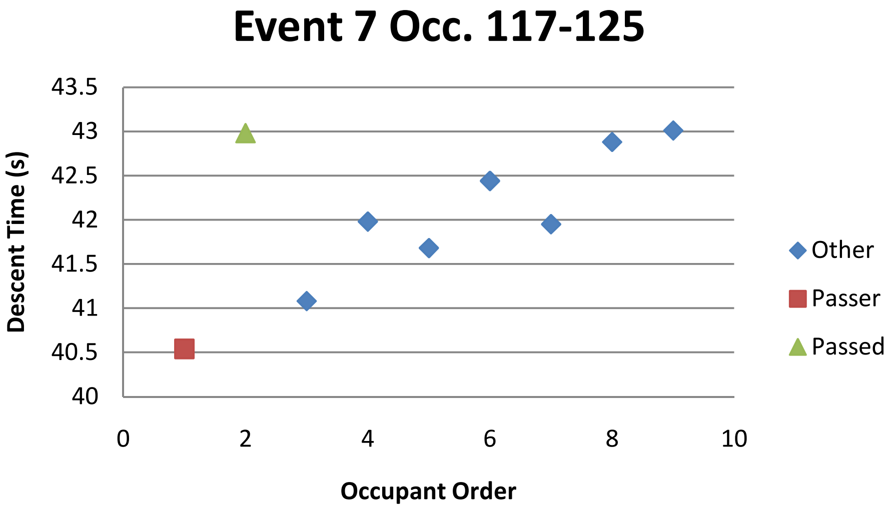


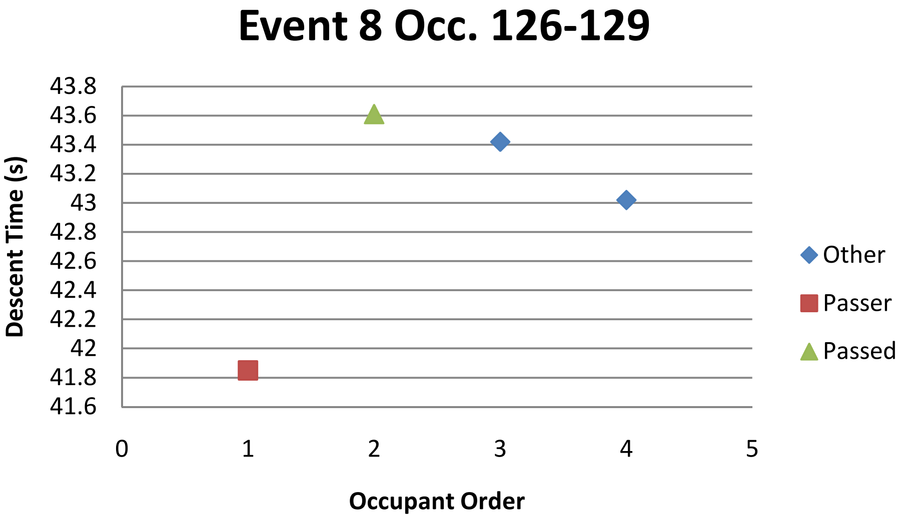

Event 3 Occ. 59-67
Descent Time (s)
45
44
43
42
41
40
39
38
0
2
4
6
8
10
Occupant Order
◆ Other
■ Passer
▲ Passed

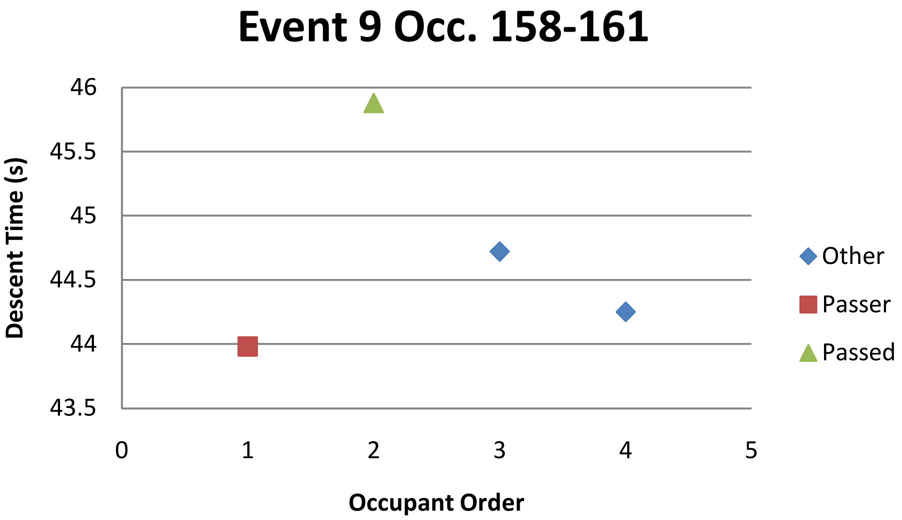

Event 4 Occ. 68-75
Descent Time (s)
42.5
42
41.5
41
40.5
40
39.5
39
0
2
4
6
8
10
Occupant Order
◆ Other
■ Passer
▲ Passed


Event 5 Occ. 76-79
Descent Time (s)
42.6
42.4
42.2
42
41.8
41.6
41.4
0
1
2
3
4
5
Occupant Order
◆ Other
■ Passer
▲ Passed


Event 6 Occ. 103-111
Descent Time (s)
40
39.5
39
38.5
38
37.5
37
36.5
36
0
2
4
6
8
10
Occupant Order
◆ Other
■ Passer
▲ Passed

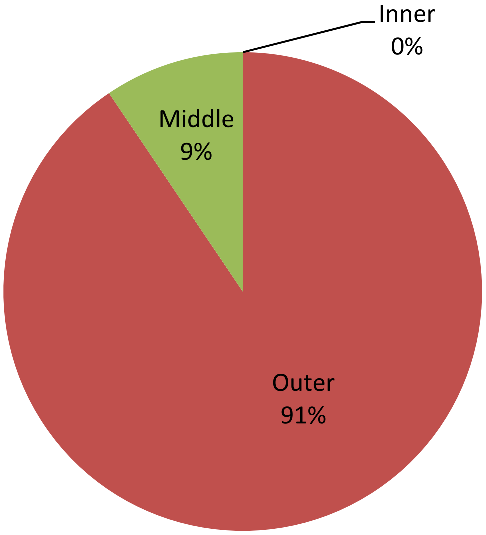

Event 7 Occ. 117-125
Descent Time (s)
43.5
43
42.5
42
41.5
41
40.5
40
0
2
4
6
8
10
Occupant Order
◆ Other
■ Passer
▲ Passed


Event 8 Occ. 126-129
Descent Time (s)
43.8
43.6
43.4
43.2
43
42.8
42.6
42.4
42.2
42
41.8
41.6
0
1
2
3
4
5
Occupant Order
◆ Other
■ Passer
▲ Passed

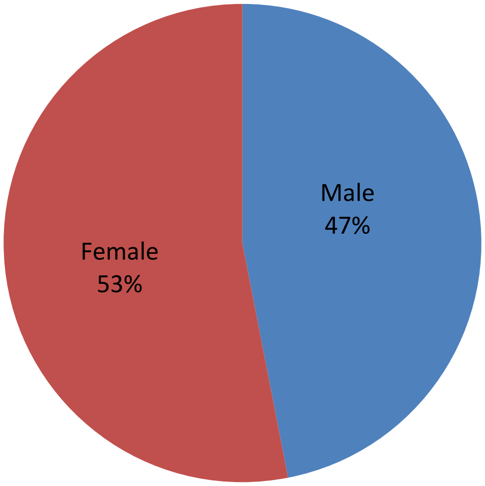

Event 9 Occ. 158-161
Descent Time (s)
46
45.5
45
44.5
44
43.5
0
1
2
3
4
5
Occupant Order
Other
Passer
Passed

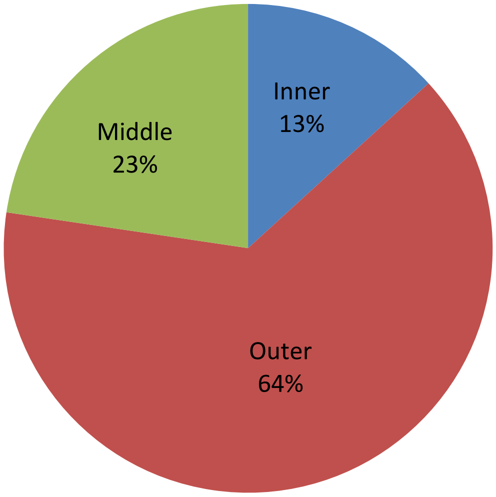
Appendix G: Merging Behavior Demographic Pie Charts

Building 4 Single-Person Mergers

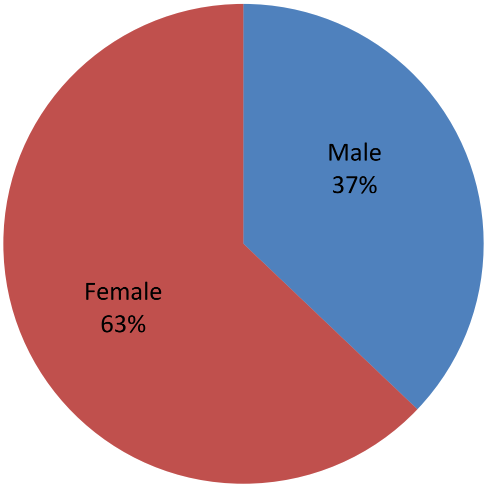


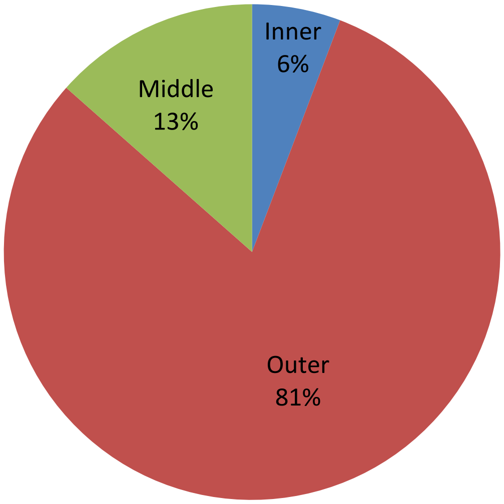
Building 4 Allow Single-Person Merge



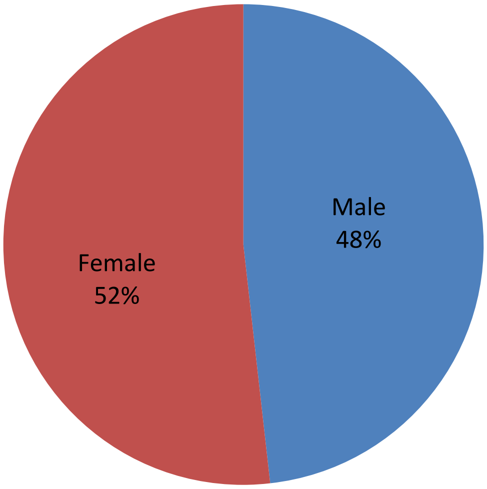


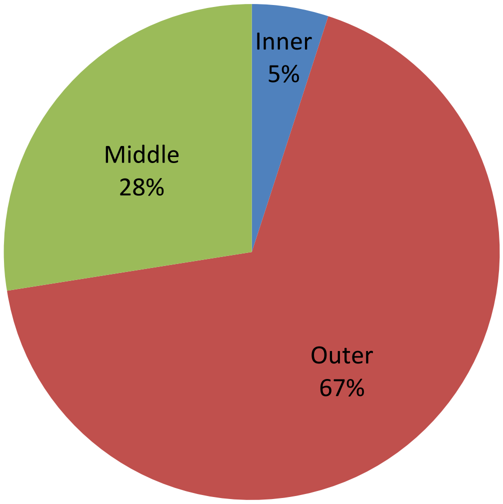
Building 4 Multi-Person Mergers



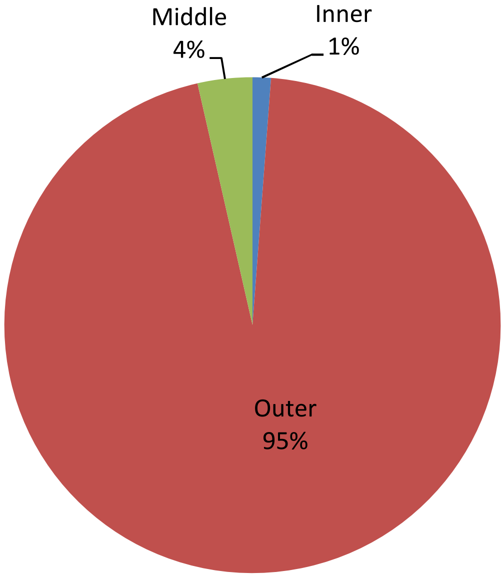


Building 4 Allow Multi-Person Merge

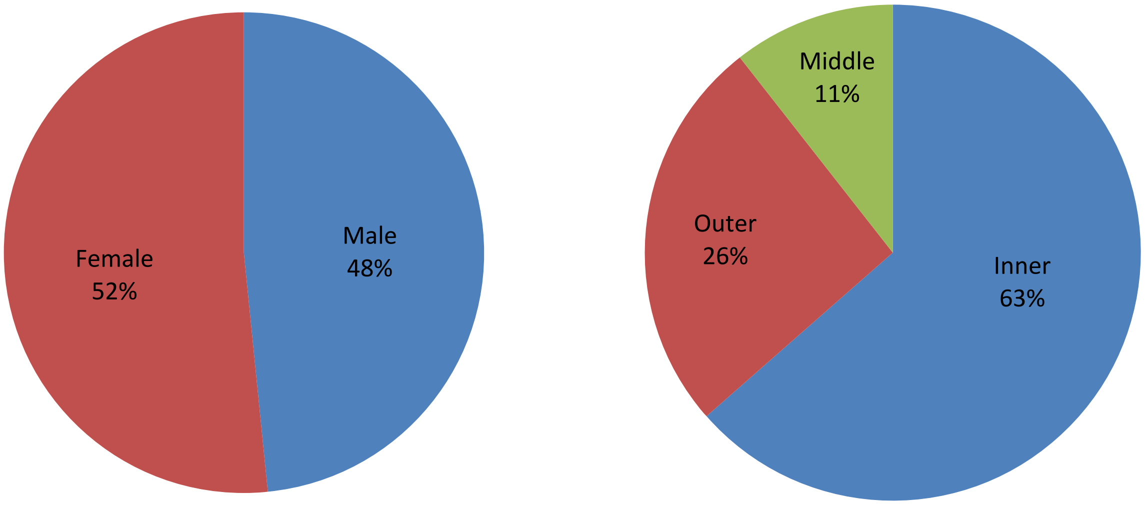




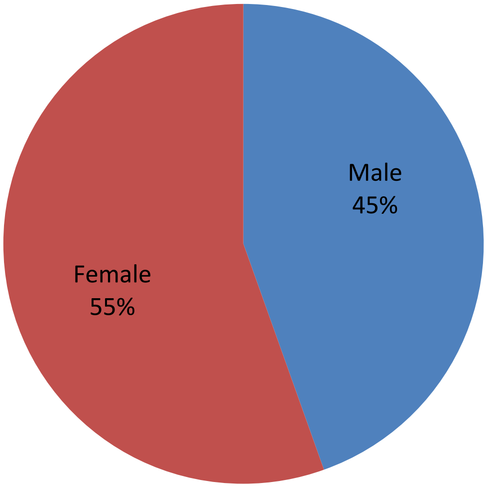
Building 5 Single-Person Mergers

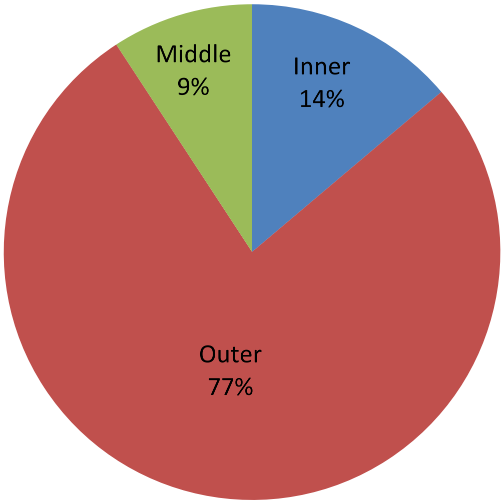


Building 5 Allow Single-Person Merge

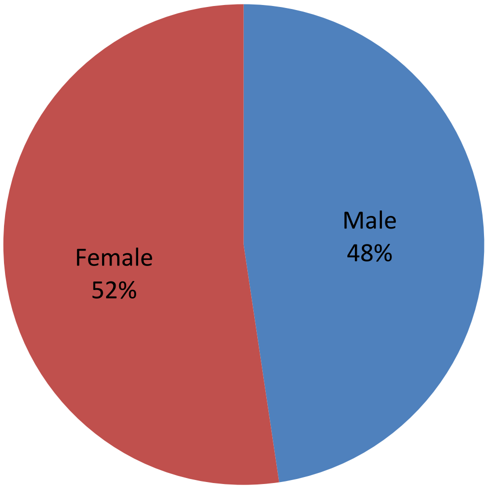


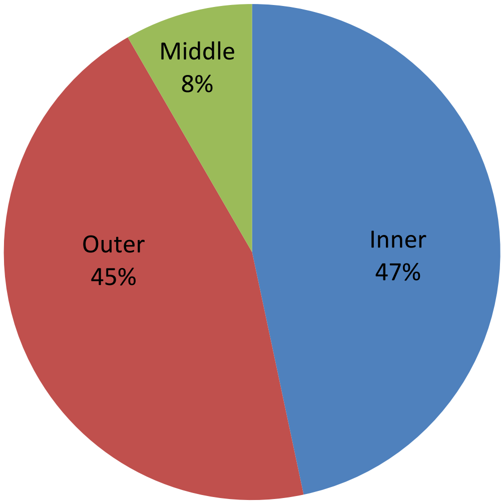
Building 5 Multi-Person Mergers



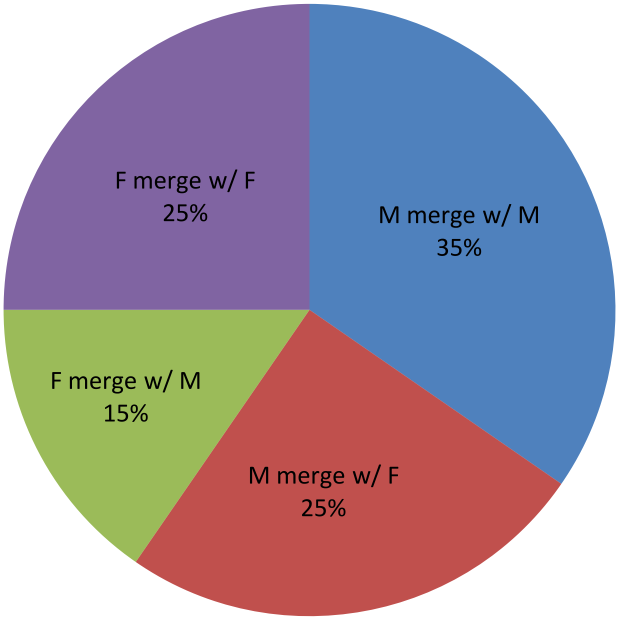


Building 5 Allow Multi-Person Merge

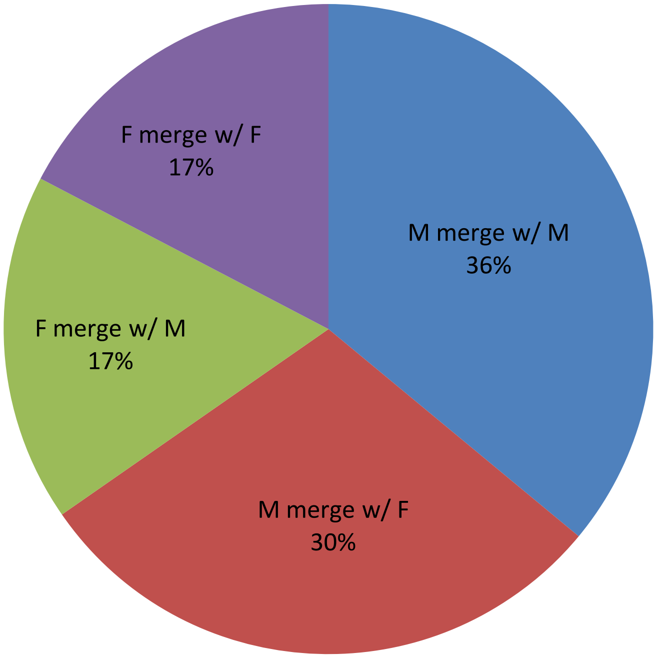




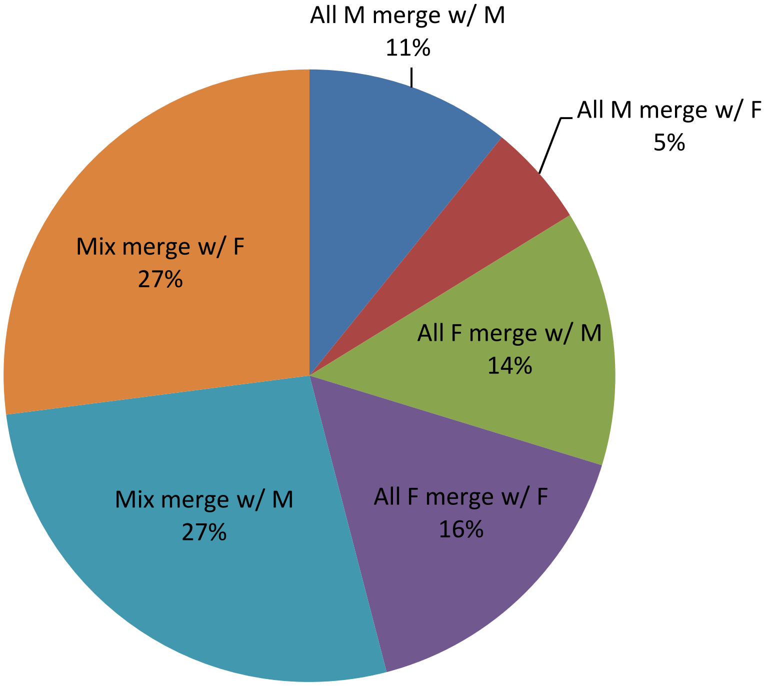
Building 4 Single-Person Merge: Who Merges in Front of Who



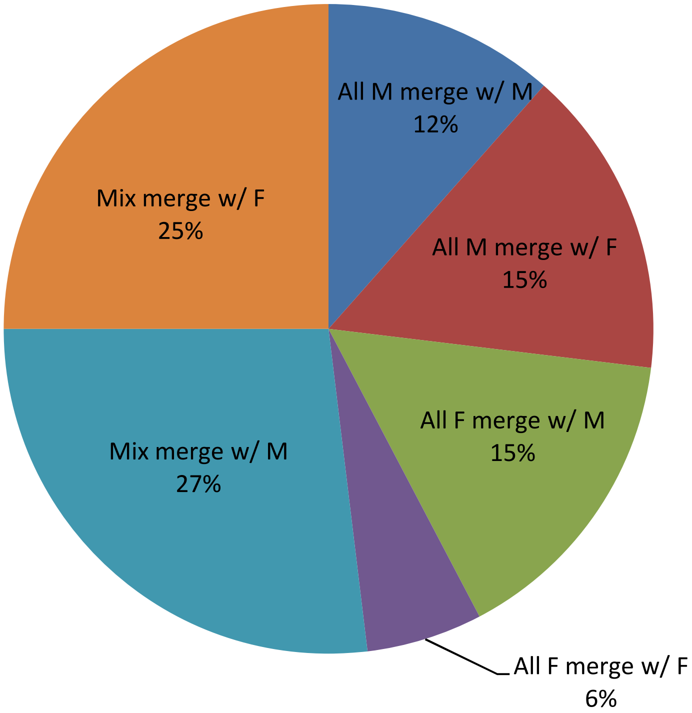
Building 5 Single-Person Merge: Who Merges in Front of Who



Building 4 Multi-Person Merge: Who Merges in Front of Who

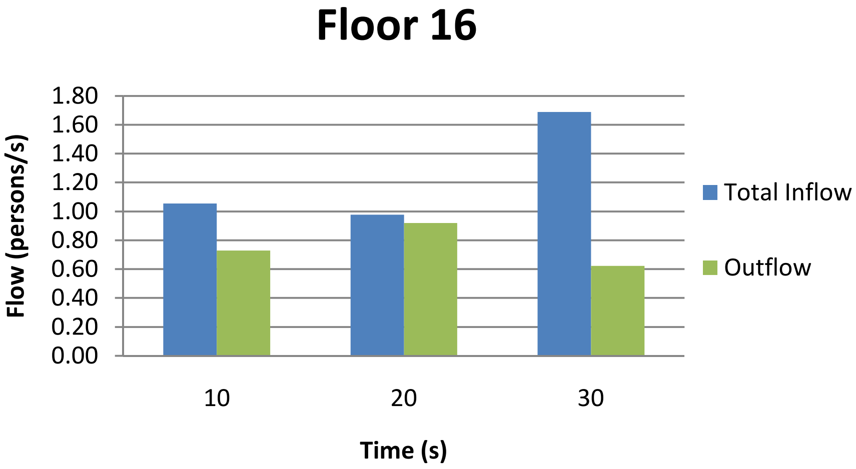


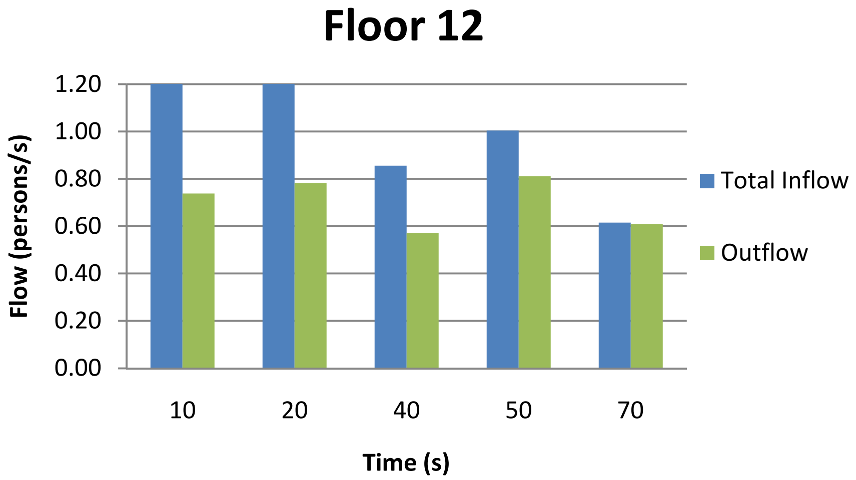
Building 5 Multi-Person Merge: Who Merges in Front of Who

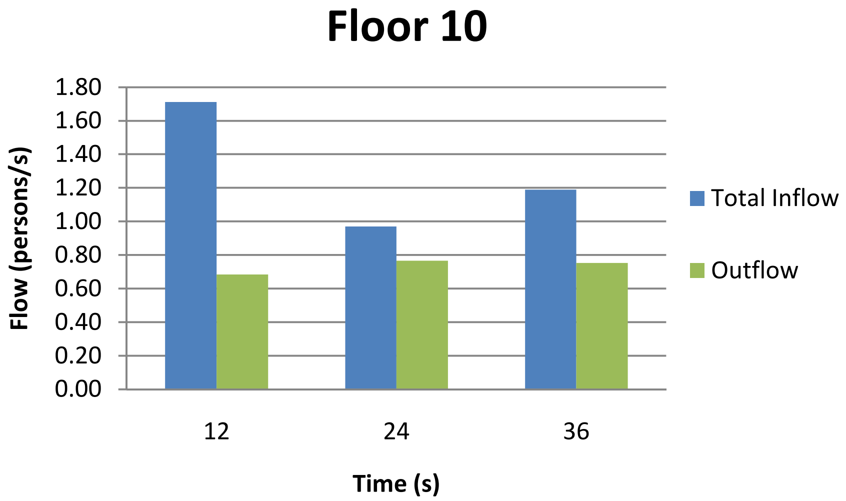


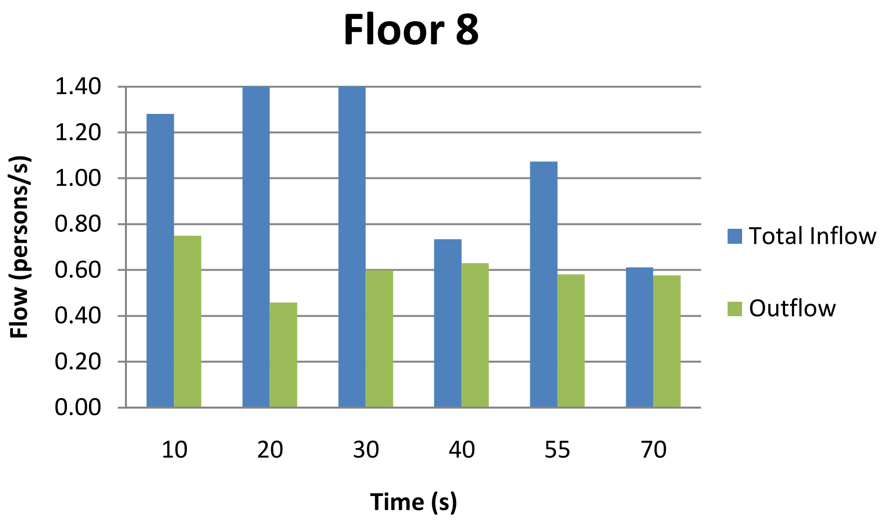
Appendix H: Merging Flow Graphs

Stair 4A

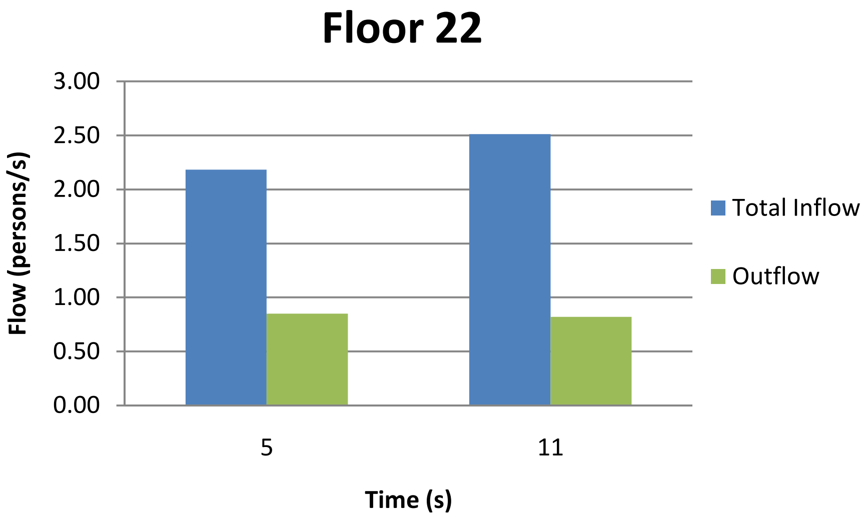


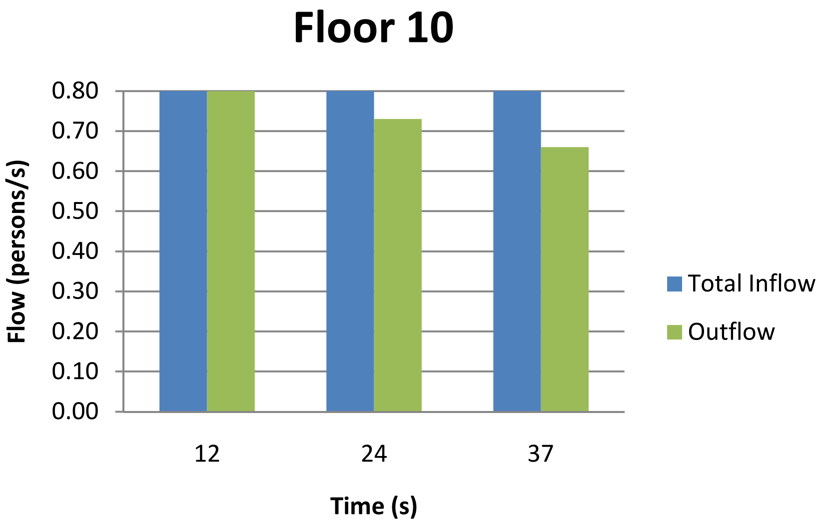


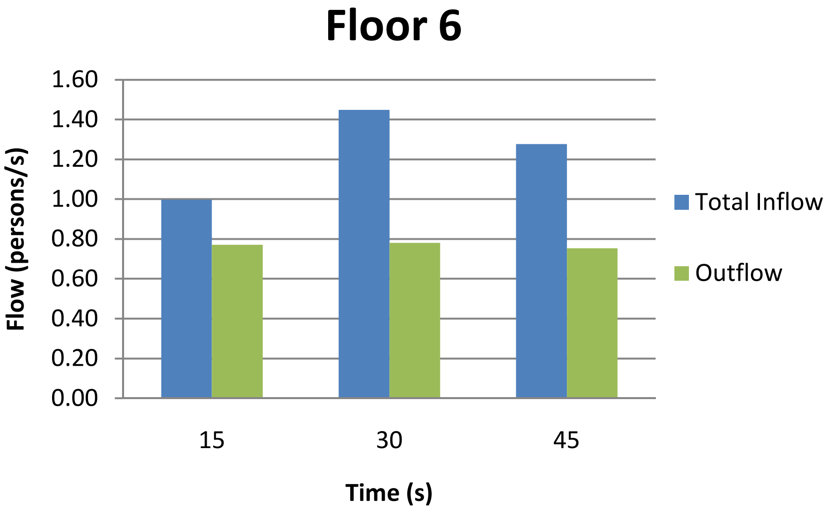


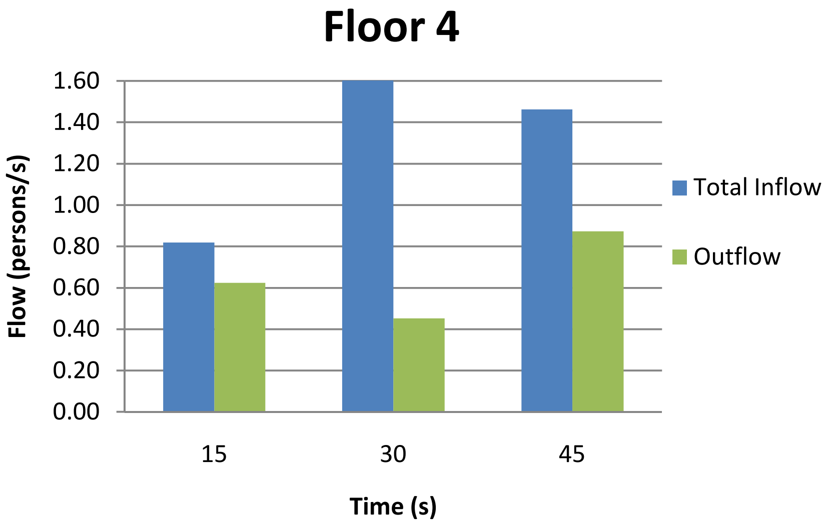

Floor 8
Flow (persons/s)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
10
20
30
40
55
70
Time (s)
Total Inflow
Outflow

Stair 4B

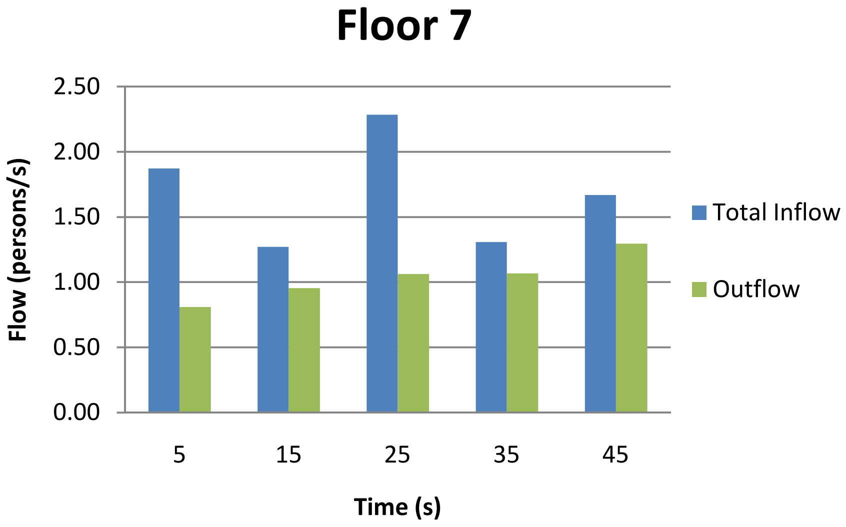

Floor 22
Flow (persons/s)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
5
11
Time (s)
Total Inflow
Outflow

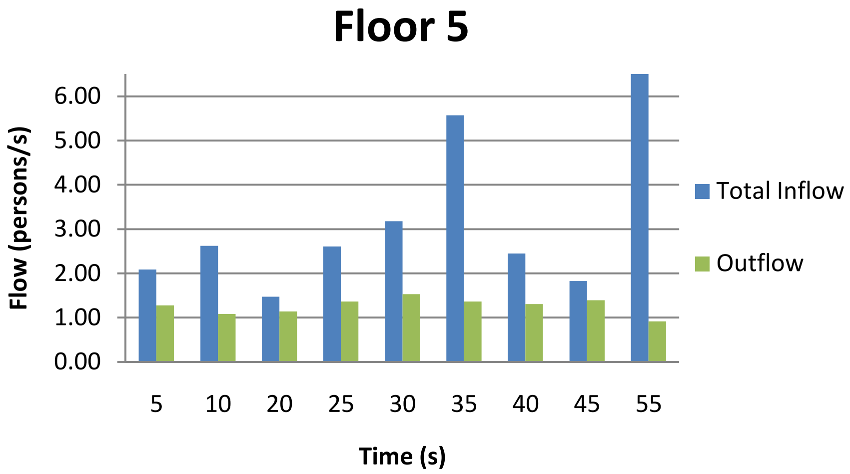

Floor 10
Flow (persons/s)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
12
24
37
Time (s)
Total Inflow
Outflow

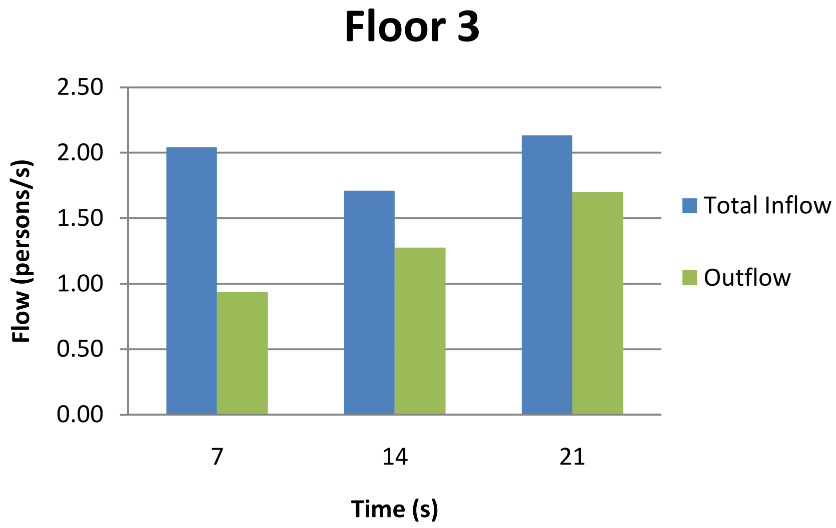

Floor 6
Flow (persons/s)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
15
30
45
Time (s)
Total Inflow
Outflow


Floor 4
Flow (persons/s)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
15
30
45
Time (s)
Total Inflow
Outflow

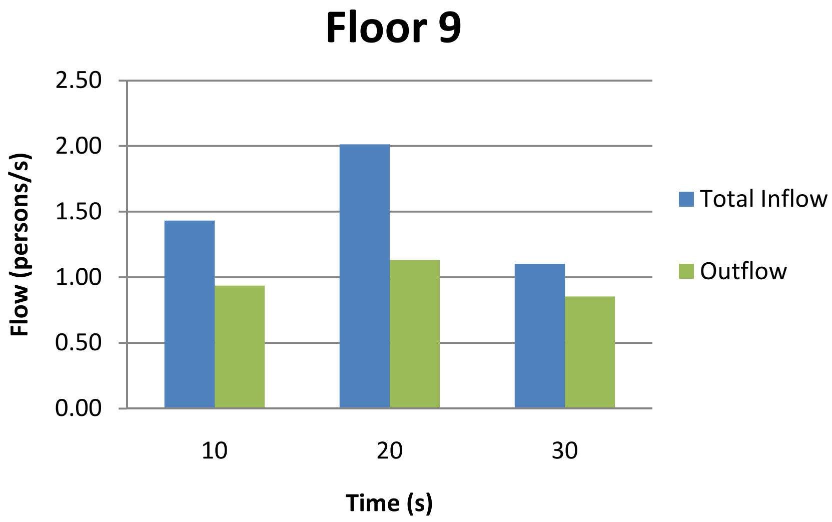
Stair 5A

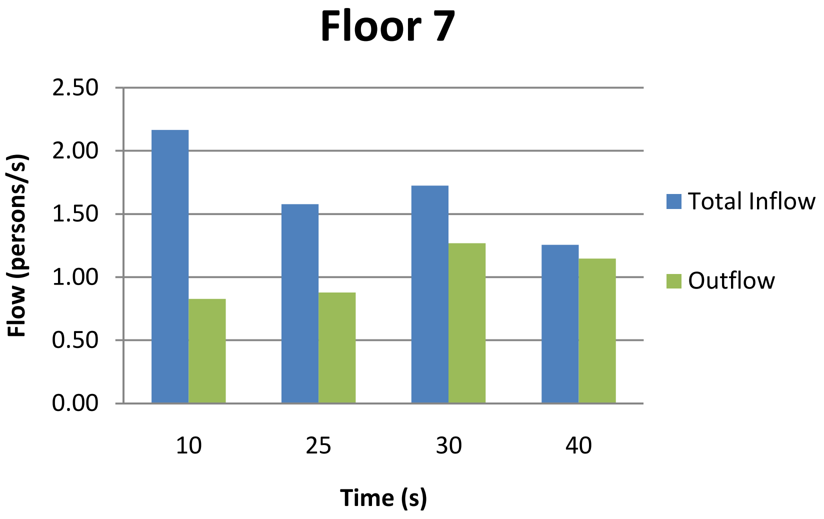

Floor 7
Flow (persons/s)
2.50
2.00
1.50
1.00
0.50
0.00
5
15
25
35
45
Time (s)
Total Inflow
Outflow

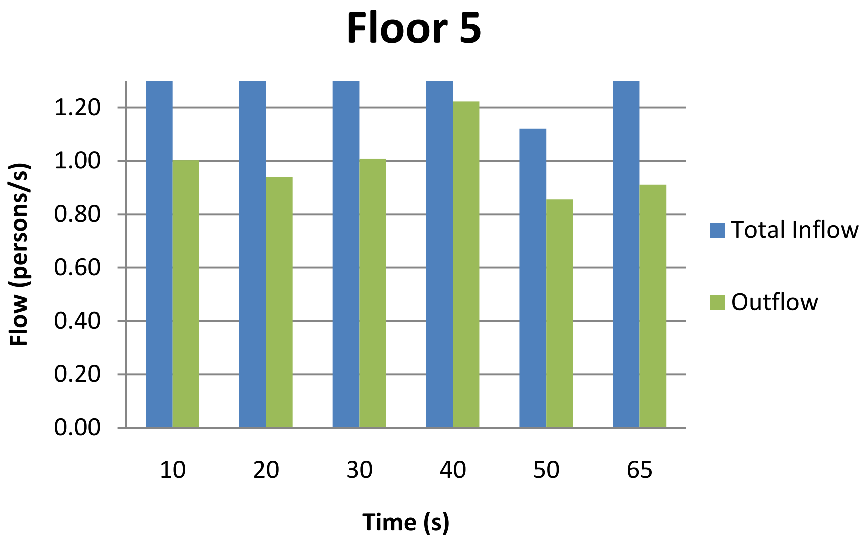

Floor 5
Flow (persons/s)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
5
10
20
25
30
35
40
45
55
Time (s)
Total Inflow
Outflow

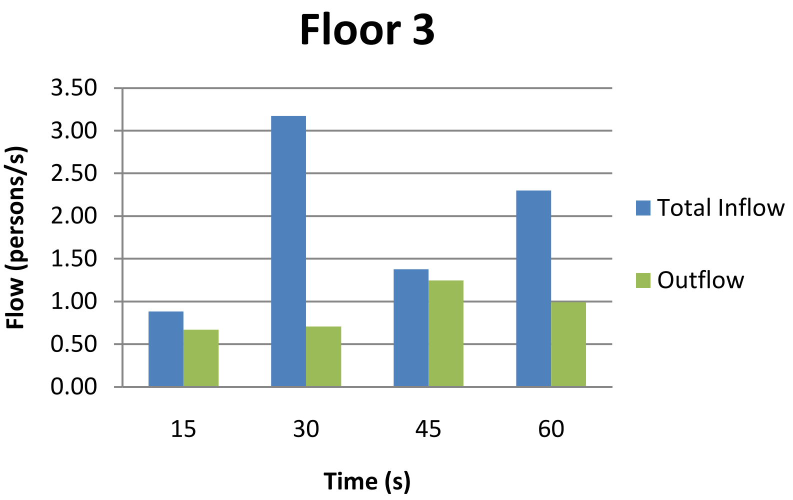

Floor 3
Flow (persons/s)
2.50
2.00
1.50
1.00
0.50
0.00
7
14
21
Time (s)
Total Inflow
Outflow

Stair 5B


Floor 9
Flow (persons/s)
2.50
2.00
1.50
1.00
0.50
0.00
10
20
30
Time (s)
Total Inflow
Outflow


Floor 7
2.50
2.00
1.50
1.00
0.50
0.00
Flow (persons/s)
10
25
30
40
Time (s)
Total Inflow
Outflow


Floor 5
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Flow (persons/s)
10
20
30
40
50
65
Time (s)
Total Inflow
Outflow


Floor 3
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Flow (persons/s)
15
30
45
60
Time (s)
Total Inflow
Outflow

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