ABSTRACT

Title of Document: OBSERVED BEHAVIOR OF PLATOON DYNAMICS DURING HIGH-RISE STAIRWELL EVACUATIONS

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This research analyzes the phenomena of grouping or platooning during the evacuation of seven stairwells within four different high-rise buildings. The purpose of this research is to investigate the changes occurring to platoons as they descend the stairs in order to incorporate the results into computer egress models. Platoons are found to travel in three distinct patterns: elongation, compression, and equilibrium. Also, platoons are found to remain unchanged, add new occupants, merge with other platoons, or fragment during their descent within a stairwell. The results demonstrate that a trend exists between patterns of platoon elongation leading to fragmentation and platoon compression leading to platoons merging. The majority of the platoons identified are found to consist of one person and remain unchanged as they descend between floors. Finally, a qualitative comparison between the platoons analyzed and the platoons identified in the behavioral computer egress model Pathfinder, is presented.

OBSERVED BEHAVIOR OF PLATOON DYNAMICS DURING HIGH-RISE STAIRWELL EVACUATIONS

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2012

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Acknowledgements

I would like to begin by expressing a special thanks to my advisor, Dr. James Milke for helping me with my research and most importantly, for being my greatest mentor through my five and a half years in the department of fire protection engineering. When I applied to the University of Maryland during my senior year of high school and declared fire protection engineering as my major, Dr. Milke immediately contacted me and invited me to make a visit to the newly renovated FPE department. On my visit, Dr. Milke took time out of his day to answer any and all questions I had and gave me a tour of the new department. After meeting with Dr. Milke I was certain that fire protection engineering was the career path for me. Over the years his concern and openness for his students and his enthusiasm and dedication to the field of fire protection engineering has been unmatched. Without his help, I would not be where I am today, and for that, I am extremely grateful.

I would also like to express my sincere thanks to Pat Baker, program management specialist for the FPE department. Pat has always been a kind friend and was always there to help me with any technical problems or scheduling conflicts. Thank you so much for everything you do.

I would also like to thank NIST for funding this research and providing me with the opportunity to further my education. Without this grant I would not have been able to pursue a graduate degree. I would like to convey a special thanks to the staff at the Fire Research division at NIST, especially Mr. Jason Averill, Mr. Richard Peacock, and Dr. Erica Kuligowski. Mr. Averill greatly supported this research and Mr. Peacock was always there to help me when I worked on the data at NIST. A special thank you is given to Dr. Kuligowski for providing me with new ideas on this research and for being my point of contact at NIST.

I would like to convey a special thank you to Dr. Bryan Hoskins and Andrew Leahy. The research of human behavior and egress of both these individuals made it possible for me to complete my thesis, and for that, I am very grateful. Bryan, you were always there by asking me how my research was going and providing me with new ways to interpret and analyze the data. Andrew, you were by far my greatest source of knowledge on the subject and were always there to answer any question I had. I am greatly thankful for your time and for helping me get started on my research.

I would also like to extend my thanks to my thesis committee members, Dr. Arnaud Trouve and Dr. Erica Kuligowski, for all of their time and input on this research. I would also like to thank Colin Miller who assisted me in finalizing the data analysis of my research.

I would like to express a special thanks to Mr. Thomas H. Seymour, fire protection engineer at the Congressional Office of Compliance. Tom, I enjoyed working with you at the Office of Compliance and appreciate all of your help and guidance. You were my first and greatest professional mentor in the field of fire protection engineering. Most importantly, you always expressed the importance of obtaining a graduate degree in fire protection engineering, and for that, I most grateful.

Finally, I would like to convey my appreciation and a heartfelt thanks to my parents. Mom, you were always there to show your love and care for me in the happiest and hardest of times. Dad, you have been the best man in my life. You were always there to keep me safe and guide me on the right path. You both are the greatest parents a child could ever have and succeeded in making me the man I am today. Your love and support cannot be measured and I am most grateful to you both for expressing to me the importance of a college education. Thank you so much for everything that you do. I love you both very much.

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Chapter 1: Introduction

The following study is a continuation of a multiyear grant funded by the National Institute of Standards and Technology (NIST) relating to occupant egress within high-rise stairwell evacuations during fire drills. Within the fire protection engineering community, one of the most widely known and widely used standards is the Life Safety Code, NFPA 101 [1]. The main purpose of the Life Safety Code "is to provide minimum requirements ... for safety to life from fire" [1]. In the event of a fire in a high-rise building, occupants should have a safe path of travel that leads out of the building. This path of travel will typically be an exit stairwell. An exit is defined as "that portion of a means of egress that is separated from all other spaces of a building or structure ... to provide a protected way of travel to the exit discharge" [1]. This study will focus only on the exit stairwells, which are the main exits for a high-rise building.

In the design of some high-rise buildings, fire protection engineers will conduct an egress analysis to determine the total time for all occupants to evacuate the building via the exit stairwells. The total building evacuation time is typically estimated with the use of the basic hydraulic model or by the use of a computer egress model. The basic hydraulic model quantifies the time of evacuation with several assumptions. This model assumes "all persons start to evacuate at the same instant," "occupant flow does not involve interruptions caused by evacuee decisions," and "the evacuees are free from impairments/disabilities that impede their movement" [2]. Therefore, the basic hydraulic model treats all individuals as uniformly moving and does not consider any other human phenomena, such as grouping during evacuations. This research aims to improve the models which calculate the egress time via the exit stairwells by highlighting the effects of grouping among evacuees.

The phenomenon of grouping or platooning has been observed in several building evacuations. It is evident after observing the data collected by NIST that individuals will form platoons as opposed to being uniformly spaced during evacuations. For this study, a platoon is defined as a group of individuals who are spatially close to each other. This research will show that platoons form often and the effects of platoon movement will be analyzed for the overall egress performance of the population.

The concept of a “platoon” has been briefly studied within the fire protection literature. However, platoons have been analyzed within the transportation engineering community for decades with regard to traffic flow theory. This study will highlight the various effects and characteristics that platoons encompass during an entire evacuation. Therefore, this paper will investigate the formation, travel, descent rate, and flow patterns of platoons.

Chapter 2: Background Information

This chapter reviews previous research pertaining to evacuation of buildings with respect to human phenomena such as platooning. Section 2.1 includes a brief discussion of how computer egress models are used within the fire protection community as well as a description of Pathfinder, a computer evacuation model. In Section 2.2, an in-depth review of the effect of social groups appearing in fire protection literature is covered. Section 2.3 contains a review of pedestrian platoons studied in public spaces, such as sidewalks. Section 2.4 provides a literature review on how platoons are viewed within the transportation engineering community with regards to traffic flow. Section 2.5 covers the two most recent high-rise stairwell egress studies which include the phenomenon of platooning. Finally, Section 2.6 includes an explanation upon the validity of the egress data used in this study.

2.1 Computer Egress Models

2.1.1 The Role of Computer Egress Models

Many computer egress models exist today which can simulate various degrees of emergency movement. Over the past couple decades, computer egress models have become more sophisticated so that a wide variety of human behaviors during evacuation can be modeled. These models aim to include the behavioral limitations which the hydraulic model does not include, such as varying walking speeds among a population [3]. Unfortunately, very little information or data is available regarding the behaviors of occupants during high-rise building evacuations [3]. Therefore, this current study provided with the high-rise stairwell evacuation data from NIST aims to provide useful input for those computer egress models which include various behavioral aspects of evacuees, such as the phenomenon of platooning.

When fire protection engineers are performing a timed egress analysis on a building or structure, they may choose to use a manual approach, empirical approach, and/or a computer model approach. The manual approach is similar to the hydraulic model where calculations of speed, density, and flow are accounted for while neglecting human behavior. The empirical approach "compares the structure in question to data collected from a comparable structure" [3]. And the computer model approach can account for a variety of evacuation scenarios while incorporating human behavior.

When engineers decide to use a computer egress model, selecting the appropriate model is very important. The computer model must be both verified and validated. Therefore, the engineer should "be aware of the group or individual who developed the model" in order to understand its abilities [3]. Also, the computer egress model must be properly verified to account for certain aspects such as fire drills, people movement, and past evacuation experiments. The results in this study will hopefully help in verifying and validating human behavior in models.

When assessing a current computer model, three different types of computer egress models are available. These models are movement models, partial behavior models, and behavioral models. Movement models "concentrate on the simulation of occupant movement" only and do not account for human behaviors, similar to the hydraulic model [3]. Partial behavior models "primarily calculate occupant movement but also simulate evacuee behavior to some degree" [3]. And behavioral models incorporate decision making processes and actions "in addition to movement toward a specific goal (exit)" [3]. This study should provide input for both partial behavior and behavior models.

Computer egress models that simulate human behavior will include one of the following four different 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)” [3].

For some of the behavioral computer models, users will be able to “specify certain behavioral actions for individuals or sometimes distribute certain probabilities of behaviors over a segment of the population” [3]. However, it is important to make sure the behaviors specified will be likely in the actual egress performance of the building being modeled. This thesis will include trends in human behavior, such as platooning of evacuees, which will be helpful in improving behavioral computer egress models.

Most of the current behavioral computer models can account for varying movement speeds among a population; however, none of these models simulate the phenomenon of platooning. The varying evacuation speeds among a population of occupants will depend on the following:

- “The distribution of men/women within the structure
- The age of the occupants simulated
- The body size of the occupants simulated
- The presence of occupants with disabilities” [3].

When using a behavioral computer egress model, occupants that are women, elderly or young, have larger body sizes, or have disabilities will be assigned slower walking speeds. As other occupants with faster walking speeds approach the slower occupants within a stairwell, a platoon of occupants may be created if the faster ones are unable to pass the slower ones. These scenarios exist within behavioral computer egress models; however, no analysis of the platoons seen within the model currently exists. This research aims to provide ways of defining and analyzing platoons which will improve results of computer egress models.

2.1.2 Pathfinder

The Pathfinder computer egress model is licensed by Thunderhead Engineering with the latest edition released in 2011. This model "provides a graphical user interface for simulation design and execution as well as 2D and 3D visualization tools for results analysis" [4]. Users may create or import a prescribed geometry of a building which is modeled in a 3D triangulated egress mesh. All occupants move on the egress mesh towards a final destination. Each occupant moves independently from other occupants and can be given a unique set of parameters such as a maximum speed and exit choice. Occupant movement speed down stairwells is reduced to a factor of their movement speed on a level surface based on the decline of the stairwell.

Pathfinder operates under two separate movement simulation modes, steering mode and SFPE mode. "In steering mode, doors do not act to limit the flow of occupants; instead, occupants use the steering system to maintain a reasonable separation distance" [4]. The steering system in Pathfinder moves occupants from their current position to a common goal while allowing occupants to respond to a changing environment and avoid collisions. Conversely, "in SFPE mode, occupants make no attempt to avoid one another and are allowed to interpenetrate, but doors impose a flow limit and velocity is controlled by density" [4]. Essentially, movement in SFPE mode is governed under the basic hydraulic model.

Pathfinder 2011 is utilized in this thesis to identify if the phenomenon of platooning occurs in a current computer egress model. A simple egress simulation involving the evacuation of a high-rise building is created to demonstrate if the effect of platooning can be replicated. The results of the Pathfinder model is also compared to actual egress data which identify the occurrence of platooning.

2.2 Social Groups in Fire Protection Literature

The observation of social groups in fire drills, fire incidents, and emergency situations is commonly mentioned. Various fire and evacuation studies (i.e. [5-20]) all mention the phenomena of social groups. It is important to note that there is a clear difference between a social group and a platoon. A social group is a group of people who know or are familiar with each other. And a platoon can be one person or a group of people who are spatially close to each other. Therefore, all social groups are platoons but not all platoons are social groups. Each of the following studies is presented chronologically in order starting with the latest.

In the 1960s, Latane and Darley studied college student's responses to smoke entering a room while the students were completing a written questionnaire. One conclusion from this study was that the presence of others in the room delayed the noticing of smoke and evacuating the room [5]. Bryan commented that "the recognition of ambiguous fire incident cues as indicators of a possible emergency condition appears to be inhibited by the presence of other persons" [6]. Therefore, the presence of a group will increase the pre-evacuation time of individuals, with regards to fire cues given, due to social interactions. However, there was no indication in this study if the group of individuals evacuated the test room individually or in a group once the smoke was reported.

Other researchers also mention pre-evacuation times for social groups. Proulx writes, “Occupants are likely to attempt to gather with people with whom they have emotional ties before starting evacuation, such as a family group” [7]. Therefore, the time it would take for an individual to evacuate would increase due to the social ties to other individuals. This also shows that once a group of individuals has gathered together, the group is likely to stay together during evacuation.

In the 1970s, Pauls studied the evacuation procedures for high-rise buildings in Canada. In his research, Pauls states “that 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” [8]. In other words, Pauls is saying that as the smaller groups of people disregard personal space, larger groups of individuals can form, which would create a high volume and flow down the stairs. Pauls also writes, “there were often large single-sex groups in the streams of evacuees (partly as a result of a ‘ladies first’ procedure at the entries to exits)” [9]. This shows that groups formed due to the gender of the evacuees in the exit stairwells. Furthermore, this observation indicates that groups of single-sex occupants entered the exit stairwell on the same floor.

Within Pauls’ research on evacuation procedures, he studied both phased and total evacuations. In his observations with phased evacuations, he mentions a “floor group evacuating ... from the top of the building downwards” [9]. This indicates that groups of evacuees formed on one particular floor, entered the exit stairwell together and descended together. Also, in phased evacuations, groups are expected to be observed from a particular floor because only selected floors are evacuated. On the other hand, during a total evacuation Pauls mentions that "there were stops and queuing as the stair was temporarily overloaded" [9]. There was no mention of groups during a total evacuation procedure during Pauls' study. This is most likely due to the large crowding and bunching of people that occurred when the stairwell became filled full of occupants. In all of Pauls' research, many observations were recorded of groups of occupants, however; he did not provide conclusive details on how these groups formed or descended the stairwells.

In 1973, grouping was mentioned by Marchant with regards to how panic may occur in fire situations. Marchant writes, "if the group of people under consideration obeys some form of collective discipline (as do troops or firemen) it is unlikely that panic would ever occur" [10]. Also, "panic can be avoided more easily if the group is, in some way, homogeneous" [10]. Conversely, Marchant later writes, "a heterogeneous group is more difficult to control but this type is more likely to be found" [10]. Furthermore, "if the leader of a group exhibits fearlessness and appears unhurried but positive he may inspire the whole group so that they believe the fire is under control and that escape can be made safely" [10]. It is clear from these remarks that most groups are heterogeneous and have a leader according to Marchant.

In September of 1984, Kagawa et al. [11] simulated a fire drill and recorded people movement within a 53 story high-rise office building in Tokyo, Japan. Of the two main exit stairwells, egress in only the east stairwell was chosen for observations. Multiple video cameras were positioned on the floors just inside and outside of the exit doors entering the stairwell. A camera was also placed outside the exit door on the ground floor to observe the final outflow of evacuees. In addition to these cameras, two observation staff members descended the stairwell each with video camera, and four other staff members walked down with portable tape recorders.

The purpose of these cameras and recorders was to observe the flow of evacuees and record the various other phenomena occurring in the stairwell, such as merging conditions at each floor. Kagawa et al. observed that “the flow of evacuating people came out in groups headed by their leaders” [11]. This observation suggests that groups of evacuees formed either on the floor or in the stairwell, and descended in a group at the direction of some leader(s). However, there was no elaboration on why these groups formed with leaders or if they stayed together as they descended the stairs.

An analysis of group formation and leadership during evacuation was conducted by Jones and Hewitt [12] from a fire incident occurring in a 27-story high-rise office building in Ottawa, Canada in 1985. These researchers interviewed forty occupants that evacuated the building as well as ten firefighters that observed evacuees descending the stairwells. A total of four case studies were presented addressing the various forms of leadership and actions of different groups. Each of these case studies explores the difference between an “emergent” (situational) leader and an “imposed” (authoritative) leader [12]. The difference between these two forms of leadership is that “imposed leadership is determined by authority or by virtue of a person’s position in the organizational hierarchy” [12]. On the other hand, “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” [12]. Therefore in this study, groups will either contain an emergent leader, an imposed leader, or possibly both.

In the first case study, a group of six evacuees consisted of one male supervisor, one other male, and four women who evacuated the twenty-third floor by using the elevator. After seeing smoke from a freight elevator, the supervisor informed three women to gather their belongings and wait in the elevator lobby. The supervisor later joined the three women along with one other male and female and proceeded to use an elevator. Although some members of the group knew an elevator was not the safest way to evacuate, they still followed their supervisor's instructions. This case is an example of imposed leadership.

The second case study involved a group of one male supervisor with two women from one room and two men from another room on the fifteenth floor. After the supervisor noticed the smoke, the group gathered together and entered the nearest exit stairwell. As the group descended the stairwell, the smoke became so thick and irritating by the fourth floor that they decided to turn back and find a floor to enter. They entered an unlocked door on the ninth floor and gathered with a few women from the cleaning staff before traveling to the stairwell on the opposite side of the building. Upon finding this stairwell filled with smoke they argued about course of action to take next. The male supervisor suggested ascending the stairs to the roof for fresh air while one male suggested putting damp clothing over their mouths and continuing downward. At this point the group split into two separate groups. The first group consisted of the supervisor with two others going towards the roof (described in the third case study). The other group consisted of one male, one female, and the cleaning staff covering their mouths with wet clothes and proceeding down the stairs. This case presented both an example of an imposed leader (the supervisor), and an emergent leader under the direction of the other male. In this case, the emergent leader led the women to the ground floor without difficulty.

The third case study consisted of the group from the second case ascending the stairs towards the roof. This group met with another group descending the stairs near the fifteenth floor. The group descending decided to join the group ascending since the smoke was becoming denser as they went down the stairs. The combined group proceeded up the stairs towards the roof and found the access door to the roof locked. At this point the group split into multiple smaller groups and descended the stairs covering their mouths with wet towels from the twenty-seventh floor. The smaller groups "descended with those with whom they were most familiar" [12]. This case is an example of imposed leadership which failed. Since the supervisor found the roof door locked, his plan for fresh air failed and the other group members made their descent without his direction.

The fourth and final case consisted of fourteen male and ten female evacuees who were distributed over eleven floors of the office building. Each of these occupants evacuated individually and "did not seek to form groups" [12]. In the organization of these individuals' work, they generally worked alone and made their own decisions. Therefore, they "had no reason to form groups or to seek leaders in order to decide on the best course of action" once they noticed the smoke [12]. This case presents a scenario where neither an imposed nor an emergent leader was present during evacuation.

Jones and Hewitt were able to make several conclusions from the interviews and observations from each case study. First, this study demonstrates "that the presence of leadership and the form that it takes do affect the evacuation strategy adopted by a particular group" [12]. Also, "both leadership and group formation are related to the fire training people receive and the normal roles they occupy in the organizational structure" [12]. Finally, if the plan of "an imposed leader failed ... a new leader emerged" [12]. These conclusions begin to clarify the actions social groups take during evacuations. They also exemplified that evacuations can consist of groups that split up and merge together, as well as individuals that evacuate by themselves.

A similar group scenario with an imposed leader was observed in a study comparing three different evacuation situations which provided validation data for egress modeling. Rinne, et al. [13] studied the evacuations of a public library, a medium sized office building, and a large office building at Helsinki University. One of the observations from a stairwell in the medium office building observed two separate groups of four and seven occupants which "followed the first person all the way down to the basement" [13]. Once they realized they went too far down the stairwell, they turned back and exited one more floor up on the ground floor. This example shows how the groups followed the direction of one specific person. However, in both of these groups, there was no split as they ascended the stairs to the exit. Although the direction of one person was followed in these groups, there was no indication of whether the leader was a supervisor or how and where the groups initially formed.

Another observation was made by Rinne, et al. in one stairwell of the large office building. "One long queue was once formed when a small group of people coming from the upper floors stopped for 60 s and allowed the flow from the office to enter the stairway" [13]. This observation was similar to the one mentioned by Pauls where groups of males allowed the females to enter the stairway first. However in this observation, there was no indication of the gender of the group or how the group originally formed.

A more recent experiment by Proulx [14] in the mid-1990s depicted social groups evacuating during a fire drill via the exit stairwell in apartment buildings. Four different apartment buildings each in a different city and ranging from 6-7 stories in height were chosen for this study. All four buildings had an average population of 150 occupants with a mixed occupancy containing children, adults, seniors, and people with disabilities. Proulx placed 12 video cameras in each building to record "such events as the time to respond to the alarm, the location, time and frequency of movements and the interaction between occupants" [14]. A local fire department participated in each study and assumed a fire was located on the 4th floor of each building.

Based on the observations from each building, Proulx decided to assign evacuees to either a “limitation” group or a “no limitation” group [14]. People of the limitation group contained such characteristics “that they walked with a cane, were slow walkers, were visually impaired or had multiple sclerosis” [14]. Other evacuees that carried children or were over 65 years old in age were also placed in the limitation group. All other occupants were placed in the non-limitation group due to their ability to evacuate easily and without impairments. Proulx found a significant difference between the groups based upon their ability to evacuate. Proulx stated, “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 the others” [14].

Proulx mentioned that “the stairs were never crowded during the evacuation” [14]. Because each building had a small number of occupants, queuing was not observed and all evacuees were able to descend the stairs without stopping. Proulx noted that “small children (aged 2-5) were among the slowest groups during the evacuation” [14]. The children were accompanied by adults and had to hold the handrail and take one step at a time which made their descent much longer. Proulx concluded that “the groups with small children would have considerably slowed down the evacuation of other descending occupants if there had been a crowd on the stairs” [14]. In 2001, Fahy and Proulx wrote, “a number of factors have an impact on the speed of movement, including characteristics of the occupants, such as age, gender, grouping, clothing and physical ability” [15]. This statement demonstrates that certain characteristics of evacuees, such as grouping, can either increase or decrease the time it takes to evacuate.

After viewing the videotapes from each building, one of the observations made by Proulx indicated “that people travelled in groups during the evacuations” [14]. Families were seen evacuating from the apartment buildings mostly in groups of two or three. Typically family groups with small children were seen staying together. However, if the family group contained older children, some of these groups would split up during the evacuation. Proulx also stated “some seniors evacuated individually” and “usually travelled in groups of two or three” [14]. The seniors “would exit their apartments and gather to discuss the fire drill and then proceed to leave the building in a group” [14].

Proulx concluded that “62% of the occupants evacuated in groups” and “group formations likely delayed the speed of movement of the group because members tended to assume the speed of the slowest member” [14]. Around the same time as this study, a similar statement was made by Sime who noted, “groups move at the speed of the slowest member of the group” [16]. These two statements clearly demonstrate that social groups that do not split up will typically travel at the pace of the slowest member. In the case of the groups with older people, Proulx found that sometimes they “tended to stop to converse rather than maintain the same speed during evacuation” [14]. Proulx’s study was important in distinguishing the different speeds of occupants and that many occupants travelled in groups, however; no indications were made on the descent rates of each group or if each group stayed together or split apart during the evacuation.

Another study by Proulx et al. [17] was conducted via questionnaires sent out to the occupants who encountered a fire incident at the Cook County Administration Building in Chicago, Illinois on October 17, 2003. This fire started on the 12th floor at approximately 5 p.m. and led to six fatalities and a dozen injuries. This building was a 36-story, unsprinklered office building where the majority of occupants were located between floors 5 to 35. Of the estimated 223 occupants who were seen exiting the building on a security camera after 5:05 p.m., 89 respondents returned a survey indicating they were in the building the evening of the fire, representing a 40% return rate for respondents.

From the surveys, Proulx et al. found that "77% of the respondents were in a group, whereas 23% were alone" [17]. Furthermore, the size of each evacuating group was calculated and is illustrated in Figure 2-1 [17]. Overall, this study provides a good understanding of the size of groups during an actual fire evacuation; however no indication was made to whether these groups stayed together or split up during the evacuation.

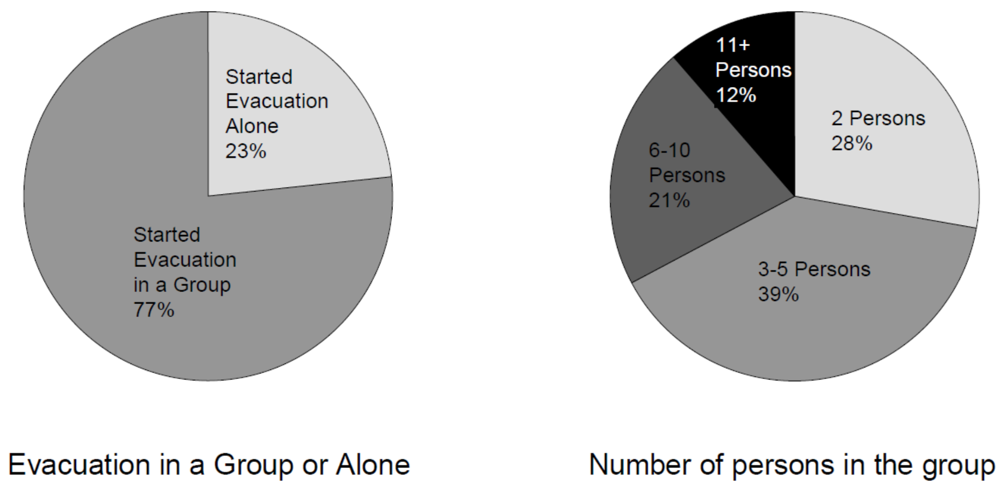

Figure 2-1: Social Interactions when Starting Evacuation [17]

During the evacuation within both World Trade Center 1 and 2 (WTC1 and WTC 2) during September 11, 2001, many groups of different sizes formed and interacted in different ways. Two separate studies of human behavior from this event (i.e. Galea and Blake [18] and Shields et al. [19]) both describe the phenomena of group behavior that occurred within WTC1 and WTC2.

Galea and Blake [18] conducted a thorough analysis of the behavior of 260 occupants that evacuated WTC1 and WTC2 from literature published in the public domain, i.e. primarily data and information printed in the media. Of the 260 occupants, 120 were located in WTC1, 119 were located in WTC2, and the remainder had an unknown origin. The majority of these occupants were reported to be "initially located on or above the 78th sky lobby" when the planes hit the buildings [18]. Many key findings from this study included aspects of group formation, composition, leaders, and cohesion.

Galea and Blake reported that before occupants entered the stairwell, 90% of the occupants from WTC1 were in groups and 88% of the occupants from WTC2 were in groups. In WTC1, groups consisted of sizes that were "evenly distributed between small (less than 5), medium (6 to 10), and large (greater than 10)" [18]. In WTC2, 90% of groups "that formed were small (less than 5 people)" and 62% of these groups involved only two people [18]. Overall, the average group size was 10.6 and 5.0 occupants for WTC1 and WTC2 respectively.

Galea and Blake also examined the composition of the groups from each building. WTC1 and WTC2 were found to have 80% and 71% of the groups composed of employees from the same office respectively. The remaining percentages consisted of groups of people from different offices. Table 2-1 [18] illustrates the composition of all the groups reported from WTC1 and WTC2.

	Number of Accounts		Number of Groups Involved	
Group Composition	**WTC1**	**WTC2**	**WTC1**	**WTC2**
Same Office	22 [35%]	34 [55%]	12 [80%]	20 [71%]
Same Office + Other Offices	5 [8%]	5 [8%]	2 [13%]	5 [18%]
Other	1 [2%]	3 [5%]	1 [7%]	3 [11%]
Insufficient Information	34 [55%]	36 [58%]		
Total	62	78	15	28

Table 2-1: Summary of Group Composition Information Excluding Unknowns [18]

Galea and Blake also noted whether the groups in WTC1 and WTC2 had a group leader. The majority of the time a group leader could not be identified in either building. However, for groups which identified a leader, 19% (12/62) of accounts described their line manager as leading groups for WTC1 and 25% (22/78) in WTC2. This data is illustrated in Table 2-2 [18].

Group Leader	**WTC1**	**WTC2**
Line Manager	12 [19%]	22 [35%]
Not Line Manager	3 [5%]	6 [10%]
No Leader	3 [5%]	1 [2%]
Insufficient Information	44 [71%]	49 [79%]
Total	62	78

Table 2-2: Summary of Group Leader Information [18]

Finally, Galea and Blake reported on the cohesion or interaction of each group as they descended the stairwell. Groups were found to expand, reduce, or remain the same in size. Groups were also found to intentionally or unintentionally split apart as well as groups that rejoined after a split. Galea and Blake reported that of groups that provided useful information 20% (WTC1) and 55% (WTC2) expanded in size and 60% (WTC1) and 40% (WTC2) reduced in size. Furthermore, 40% (WTC1) and 20% (WTC2) of the groups intentionally split and 20% (WTC1) and 5% (WTC2) of the groups unintentionally split during the evacuation. The data of group cohesion is illustrated in Table 2-3 [18].

	WTC1	**WTC2**
# of Groups that provided useful information	10	20
# of Groups that did not provide useful information	21	42
Expanded	2 [20%]	11 [55%]
Rejoined	1 [10%]	0 [0%]
Intact	4 [40%]	4 [20%]
Reduced	6 [60%]	8 [40%]
Intentionally Split	4 [40%]	4 [20%]
Unintentionally Split	2 [20%]	1 [5%]
[] represents percentages of the population for which information was available		

Table 2-3: Summary of Group Cohesion during Evacuation [18]

In 2009, Shields et al. [19] reported on the behavior and evacuation experiences of six people who evacuated WTC1 and WTC2, five of whom claimed to have mobility impairments. These six participants (labeled A-F) were interviewed after the 9/11 fire incident and a detailed description of the occupant's evacuation was described. Participants A through E were located in WTC1 and participant F was located in WTC2. Within this study, group behavior was described for each occupant with regard to "how groups formed, how they functioned and the social interactions that occurred in group formations and behavior" [19].

Participants A, C, D, E, and F all reported to have some mobility impairment, while participant B had no obvious impairment. Participants A and E both had knee surgery previous to the fire incident. Participant E could only walk short distances and had to use a cane or a scooter for long distances. Participant C had a sprained ankle incurred before the fire incident. Participant D was reported to have many ailments including pain from a hysterectomy surgery and lower back pain. Finally, participant F "was paralyzed in his left leg and suffered from hypertension" [19].

After the plane impacted WTC1, participant A gathered with some colleagues on the 64th floor and decided to evacuate. However, participant A "went back to her work station to collect some personal belongings" [19]. Then, participant A "followed the crowd" and descended the stairwell with a large group of people she did not know personally [19]. Therefore, participant A first gathered in a social group and later became part of a large crowd evacuating the building. Overall, there was no detailed information on whether participant A stayed with the crowd during the entire evacuation or whether she passed or was passed by others.

Participant B gathered with a nearby colleague and helped people find their way to the stairwells on the 63rd floor of WTC1. Eventually, participant B left his colleague to search for others and evacuated. Participant B reported that he “met people in the stairwell he knew and he chatted to them as they made their descent” [19]. However, there was no indication on how he formed with this group in the stairwell or if the group remained together during the entire evacuation.

Participant C, who was a supervisor on the 54th floor of WTC1, gathered with other supervisors and colleagues to form a group of 12 to 13 people. This group remained cohesive as participant C acted “as an authority figure” and “dissuaded a colleague from going onto a floor to see what was going on” [19]. However, at some point during the descent, participant C split from the group and moved much faster down the stairwell. He said, “I definitely passed people from floor 16 down ... there was no reason for me not to go as fast as I could” and “I shouldn’t just move slowly for fellowship” [19]. This shows that participant C first formed a social group of colleagues, then later split apart and descended the stairs much faster than the others in the original group.

After the impact on WTC1, participant D “told colleagues to get out of the building and they left together” on the 17th floor [19]. When they arrived at the stairwell, the group split up and participant D was left with only one other colleague who stayed together during the entire evacuation. The two individuals could smell jet fuel fumes in the stairwell and encountered a queue at some point during their descent. Eventually this queue of people had to turn back to find another way out of the building. Participant D and her colleague found their way out via another exit stairwell. This group was similar to the group with Participant C where they split up at some point during the evacuation from the initial social group.

Participant E knew of her impairments and “was afraid of falling over in as she put it ‘a stampede on the stairs’. So she formed a group with three colleagues who surrounded her as a protective shield" [19]. This group made their descent together from the 20^{th} floor of WTC1 and rested at times before exiting the building. Overall, this group remained together due to the impairments of participant E who needed help during her entire descent down the stairs.

Participant F was located on the 79^{th} floor of WTC2 and reported that he "saw the aeroplane flying in at eye level and hitting Tower 1" [19]. He ran went up and down floors 79-82 on more than one occasion telling people to leave the building. On floor 81, someone told him to take people with him and evacuate. Participant F took the lead of his group and got them to the 66^{th} floor where an announcement was made that it was safe to go back to work. However, he disregarded this announcement and they continued down the stairs. Around the 62^{nd} floor participant F encountered a woman "who needed help and he almost carried her down" [19]. This group stayed together during the entire descent down the stairwell. This situation was similar to the group of participant E, except participant F did not originally gather with the individual who needed help. Although there was no indication of how large this group was, they were reported to stay together during the evacuation.

Shields et al. concluded that "two types of groups have been distinguished in this paper, i.e. primary and affiliate groups, and there is evidence of group fragmentation" [19]. A primary group is formed by someone who knows they have impairments and needs help to evacuate. An affiliate group is a social group which forms before entering the exit stairwell.

Kratchman conducted a recent study which included observations of social groups [20]. Kratchman investigated the effects that firefighter counterflow caused on evacuees within a six-story building. She also highlighted the effects of nonadaptive and normal human behaviors caused on the overall evacuation. Such human behaviors included interactions with firefighters, carrying objects, and socializing. Kratchman's observations on social groups and the overall performance of the evacuation are summarized as, “traveling in a social group may not be considered to hinder evacuation, but it is important to note how people tended to travel” [20]. She also stated, “there were even cases where the occupants slowed down because they were socializing in the stairwell and then when they resumed their movement they dramatically increased their speed, which subsequently increased their overall (or average) speed” [20]. This demonstrates that a social group can slow down an evacuation, but when the group stops socializing, the overall speed is increased.

Kratchman observed nonadaptive behavior in a group of 6 occupants that re-entered a building during an evacuation. These six individuals all entered the exit stairwell together and re-entered the floor. Over a minute later they re-entered the stairwell and “were functioning as a group of individuals making decisions together” [20]. Kratchman also observed 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” [20]. This social group demonstrates that an evacuation can be slowed down as others were blocked when this group re-entered the stairwell. Although Kratchman made clear observations on how social groups affected the speed of an evacuation, no indications were made on how these groups formed or if they stayed together or split up during the evacuation.

All of the previous studies (i.e. [5-20]) identifies that social groups exist in the evacuation of buildings during fire drills and fire situations. Proulx [7] identifies how these groups gather together before evacuation. Others researchers [9, 11-14, 20] provide details on how these groups act and travel in the exit stairwell. Some studies [9, 12, 14, 17-19] even identify the composition of these groups and note if they remain intact during their evacuation. This thesis aims to provide an understanding of the dynamics of these social groups by comparing them to platoons identified in current egress data.

2.3 Pedestrian Platoons

Prior to social groups being studied in the fire protection community, platoons of pedestrians traveling in public spaces such as sidewalks were studied. The concept of a platoon of pedestrians was first used by Pushkarev and Zupan ([21] and [22]) in the 1960s and 1970s. They studied pedestrian movement in public spaces and developed useful input for the design of places such as stairways, building entrances, sidewalks, escalators, etc. Their research focused on density, speed, and flow relationships with respect to human space and aided in improving standards for walkways such as sidewalk widths. Pushkarev and Zupan note the phenomenon of platooning and its effect on pedestrian movement.

During the time period of 1960-1970, Pushkarev and Zupan observed human movement within central business districts of the midtown Manhattan area of New York City. These observations were made along several long streets with the purpose of developing methods to design better central business districts for maximum pedestrian travel. When quantifying their observations into data, they noticed that the values were widespread and weak correlations existed for pedestrian walkway spaces. Pushkarev and Zupan stated, "the short-term fluctuations due to platooning" were the direct cause of the errors and weak correlations in their data [21]. It was noted 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" [21]. Therefore, as street lights change, people are forced to stop and wait for the signal to change in order to cross a street. As the pedestrians are waiting, others approach the same intersection and a large platoon can form. This platoon will increase the density of people on the street and reduce the sidewalk space. Once the light changed and the platoon was able to cross the street, the sidewalk space increased and the platoon began to shrink in size.

In 1975 Pushkarev and Zupan [22] provided more details on pedestrian movement and space in urban areas after more observations were taken of Midtown Manhattan. Aerial helicopter photographs provided more useful input for speed and density of pedestrians as well as the phenomena of platooning. In this research, Pushkarev and Zupan were able to identify how platoons form given passing behavior, public transportation, and traffic signals. “First, if passing is impeded because of insufficient space, faster pedestrians will slow down behind slow-walking ones, and a random bunch of pedestrians soon snowballs into what can be called a platoon” [22]. Second, public transportation systems such as “subway trains, and to a lesser extent, elevators and buses release groups of people in very short intervals of time” which create platoons [22]. Finally, street lights and “traffic signals release pedestrians in groups, which tend to proceed as groups along a sidewalk” [22]. Therefore, the short-term fluctuations caused by public traffic flow created pedestrian platoons. Pushkarev and Zupan also noted, “platoons represent involuntary groupings of pedestrians and as such should be distinguished from groups that walk together by choice” [22]. Therefore, their study on platoons of pedestrians disregarded social groups.

Based upon the observations by Pushkarev and Zupan, the duration of platoons was found to be 5 to 50 seconds on sidewalks and up the stairs from subway stations. However, there was no data or observations made for platoons traveling down the stairs. Pushkarev and Zupan also noted that 53 to 84% of pedestrians travelled in platoons on sidewalks. For subway station stairs, the values increased to 75 to 95%. These percentages reflect 58 observations made during the morning and evening rush hours as well as the midday lunch hour. Furthermore, from these observations Pushkarev and Zupan were able to develop an equation which calculated the maximum specific flow of a platoon (F_p) relative to the average specific flow (F_a) of a population [22]:

$$F_p = 0.22 + F_a \tag{3}$$

For this equation, the platoon flow and the average flow are in units of people/m-s. For equation 3, Pushkarev and Zupan suggest to ensure a platoon flow rate of less than 0.33 people/m-s or a space allocation of more than 3.72 square meters per person in platoons, the average flow rate must drop below 0.11 people/m-s and the average space allocation must rise above 12.08 square meters per person [22]. Although Pushkarev and Zupan's observations were useful for public spaces and sidewalk, no equations or indications were given on how people would descend stairs.

Also in 1975, Templer [23] made observations of platoon movement in his dissertation on stair shape and human movement. Templer researched various aspects of stairs such as safety, geometry, space, erosion, capacity, and limitations. Similar to Pushkarev and Zupan, Templer made his observations in public places, such as subway stations in New York City. On the topic of platoon movement, Templer stated, "people often approach the stair in platoons as each train discharges its passengers. However, as the users approach at different speeds, the platoon builds up from a wedge, and then dies away" [23]. Templer noted that platoons have an impact on the instantaneous flow rate due to the short burst of people exiting a train. Then the flow rate diminishes as the platoon fades away.

Templer also stated, "it is not incorrect to assume that the movement patterns of several people and platoons follows many of the habits manifest by individuals. However, as stair density increases, users progressively take over as much of the stair as they need, so long as this does not interfere with the rights of people moving in the other direction" [23]. This observation indicates that platoons will spread apart with the width of the stairs as long as other people are not travelling in the opposite direction. Templer is suggesting that groups of people may be involuntarily forced together if there is an opposing flow.

Templer concluded, "if the user was part of a platoon whose members reached the stair as a group, then the user and the platoon invaded and captured as much space as was needed" [23]. Unlike Pushkarev and Zupan, the observations of pedestrian platoons made by Templer regarded people ascending and descending the stairs. The observations of Pushkarev and Zupan as well as Templer indicated how platoons formed and flowed to and from stairs; however no observations were given concerning whether the platoons stayed together or split apart after ascending or descending the stairs.

A more recent study was conducted by Gates et al. [24] on the design of traffic signal timing with respect to walking speeds of pedestrians. This study analyzed data from 1,947 pedestrian crossing events at 11 different intersections in both Madison and Milwaukee, Wisconsin. Gates et al. accounted for the effects of group size, age, sex, disabilities, and traffic conditions on the walking speeds of pedestrians. Groups in this study were defined "as two or more pedestrians crossing the street at the same time who appeared to be friends or associates" [24]. Therefore, only platoons of social groups were considered for this study. For this study, group size was separated into three categories based upon the size of the group: individuals, groups of two to four people, and group of five or more people.

From the observations, Gates et al. found that large groups of pedestrians "tended to break apart into smaller groups soon after stepping off the curb" at an intersection [24]. Also, when the groups got large at the intersection, it was very difficult to distinguish between the smaller groups when they broke apart. Gates et al. also calculated the average walking speeds as the pedestrians crossed the intersection with respect to the group size. They noted that "group size had an inversely proportional effect on walking speed" [24]. Individuals were found to walk at an average speed of 1.44 m/s, groups of two to four had an average speed of 1.32 m/s, and groups of five or more had an average speed of 1.25 m/s. Therefore, platoons of pedestrians travelled at slower speeds as the group size increased.

Gates et al. concluded that the pedestrian clearance time of an intersection was increased if more groups were expected to cross the intersection. They suggested that walking speeds of 1.16, 1.13, and 1.10 m/s were expected if groups of two to four pedestrians made up 0 to 20%, 20 to 50%, and more than 50% of the time, respectively. Furthermore, if groups of five or more were expected more than 20% of the time, a walking speed of 1.07 m/s should be expected for clearance of the intersection. These conclusions indicate that large groups of pedestrians walk slower; however the differences in these speeds are minor. Although Gates et al. made clear indications that larger groups of pedestrians travel slower, their data was only limited to social groups. Furthermore, this study had no observations on whether the groups would stay together or split apart after they cleared the intersection.

2.4 Platoons in Transportation Literature

The concept of a platoon not only refers to pedestrians or social groups, but can be considered when examining transportation movement of vehicles. However, in traffic flow, people operating their vehicle typically will not know other drivers. For the following studies on platoons of vehicles, there is no way to distinguish whether other drivers are remaining in a cluster of vehicles based upon a social relationship. Therefore, all groups of vehicles are considered to be in a platoon regardless of whether they know the other drivers or not.

Within the transportation engineering literature regarding traffic flow, various models are presented to analyze all the phenomena occurring with moving vehicles. Most of the models regarding platoons of vehicles determine traffic queues (highway jams) and road capacity. These models can be either macroscopic or microscopic in nature. A macroscopic model provides an overall view of a highway or road with set parameters (i.e. speed, density and flow), similar to the hydraulic model for evacuations. In contrast, microscopic traffic models are more complex, considering individual vehicles and the interactions between different behaviors of drivers. When examining the mathematics used in traffic models, they can be grouped into four categories:

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" [25].

These traffic flow models are similar to computer egress models in which a population is studied with specified behaviors and a certain outcome is achieved. In traffic flow models, designers must account for external forces such as the "shape, status, and wideness of the road", as well as density, surrounding structures, and the time of day [25]. These similar external forces in computer egress models include the geometry and density of the stairs, as well as the time when the stairs may be used. Realistic traffic flow models must also account for "the kind and habits of the drivers" which is similar to the behaviors of evacuees in computer egress models [25].

When traffic conditions are heavy, the model may be improved by each of the following:

1. "Introducing upper threshold values for each lane densities;
2. Phenomenologically modeling position and velocity correlation factors;
3. Taking care of the local dynamic by introducing the various maneuvers' characteristic times and thresholds;
4. Enhancing the time dependence behavior by using a scheme with memory" [25].

Each of these aspects could similarly be applied to a computer egress model as an improvement. Knowing the upper thresholds of the stairwell density and modeling evacuees' positions and velocities can improve the model. Also, understanding evacuees' maneuvers/behaviors as well as the time dependence for the behaviors will improve the model.

As early as 1969, Robertson [26] developed a traffic model named TRANSYT, or "traffic network study tool". The object of this digital traffic computer model was "to find automatically the best timings with which to coordinate the operation of a network of traffic lights" [26]. TRANSYT "contains a mathematical model which has proved to predict accurately the average number of stopped vehicles within a network of traffic lights under a given set of flow levels" [26].

In developing TRANSYT, Robertson "carried out observations at four sites in West London on the behavior of over 700 platoons" [26]. These platoons were formed as vehicles approached a traffic stop signal (i.e. a red traffic light). Once the traffic signals allowed the drivers to proceed forward, Robertson found that "a platoon of traffic will spread in time and alter in shape" [26]. The original platoon was found to break apart into smaller platoons depending on different speed of individual drivers. This traffic situation is similar to the dissipation of a queue in a stairwell. Once the evacuees are able to move down the stairs the individual speeds of people will create smaller platoons by holding back others who intend to walk faster but cannot pass the slowest member.

In 1980, Michalopoulos and Pisharody conducted further research on traffic platoons using a simple traffic flow model known as Greenshield's model. Unlike the research of Robertson who only focused on platoon dispersion after a traffic signal, Michalopoulos and Pisharody accounted for the downstream flow of platoons before traffic signals. Robertson's TRANSYT model was clearly macroscopic in nature and assumed an average travel time when focusing on platoons. Therefore, Michalopoulos and Pisharody assumed that accounting for the downstream platoon flow would help to better improve traffic signal coordination.

After using the Greenshield model with a simple north-south and east-west intersection shown in Figure 2-2 [27], Michalopoulos and Pisharody found that as a "platoon enters an area of lower density it tends to diffuse and, conversely, at higher densities it is compresses" [27]. In other words, as platoons travel away from a traffic signal they elongate and as platoons approach a traffic stop signal they compress. Although the compression of traffic platoons is artificially created by the timing of the traffic light, similar scenarios occur when queues exist in high-rise stairwells. As platoons descend a high-rise stairwell, they will compress if they encounter a queue in the floors below. Likewise, it would be expected that platoons would elongate after a queue has dissipated.

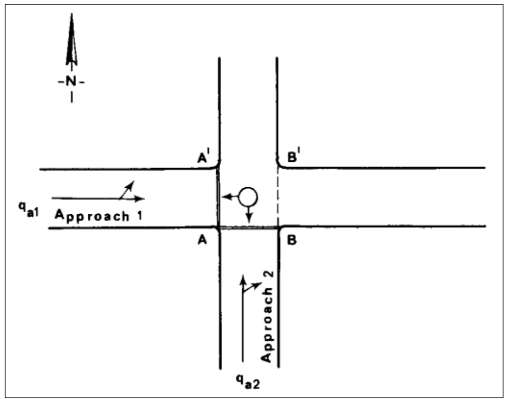

Figure 2-2: Approaching Platoons at a North-South and East-West Intersection [27]

A much more recent study of traffic platoons was conducted by Shiomi et al. [28] in 2009. They collected data from video cameras placed "at two different points on a divided two-lane, two-way section of the inbound Tokai-Hokuriku expressway" [28]. Data was collected from 2:30 to 3:30 p.m. on July 18, 2004 where 657 vehicles were observed. A second data set was collected the following day from 2:45 to 3:45 p.m. where 1,123 vehicles were observed. Both data collections were made in clear weather and it was assumed that the differences in the observations did not affect platoon formation. For this study, a platoon was "defined as a group of vehicles traveling together, either voluntarily or involuntarily, because of signal control, geometrics, or other factors" [28]. Furthermore, Shiomi et al. assumed "that platoons form stochastically because of the differences in desired speeds as well as randomness in arriving at the target section" [28].

After viewing the data collected, Shiomi et al. found that platoons were created "by slow vehicles that form moving bottlenecks" [28]. Consequently, vehicles with higher desired speeds catch up to the slow vehicle and are forced to follow it. Also, if the lead vehicle accelerates or decelerates, the speed change propagates back and the traffic flow changes within the platoon. Furthermore, after Shiomi et al. analyzed the data, a model was developed for platoon formation and speed transitions for a single-lane expressway. Their model accounts for each vehicle's individual speed and driving behavior, and can predict platoon formation for single-lane expressways. However, this model assumed the lead vehicle of a platoon to have a constant speed, which was not realistic. Furthermore, the research and traffic model of Shiomi et al. focused on a single-lane road only. Therefore, more research needed to be "expanded to depict traffic phenomena on multilane expressways, including lane-changing and overtaking maneuvers, and other types of bottlenecks such as merging sections" [28].

Overall, traffic platoons are very similar to platoons of people. Typically, a slower person may hold back people which can create a platoon. Furthermore, when large crowds of people create queues and blockages, large platoons can form similar to traffic platoons. Also, driving behaviors and walking behaviors can be similar depending on if someone is distracted and slows down or if they are in a hurry and want to pass another. On the other hand, there are designated lanes on highways which may not be included on sidewalks or stairwells. Therefore, more passing behaviors could occur in stairwells and sidewalks if there is enough room and no opposing flow. Also, people driving in vehicles need more personal space because they do not want to bump into another vehicle and cause an accident. Conversely, if someone bumps into another person on a sidewalk or stairwell, it would not be as serious of a problem. Finally, people on the sidewalks and stairwell are able to talk to each other, as opposed to those driving vehicles.

2.5 Platoons in Fire Protection Literature

Two recent egress studies by Leahy [29] and Hoskins [30] were conducted on the same NIST data used for this thesis. Both Leahy and Hoskins defined platoons based upon a spatial separation of occupants and concluded with observations on how platoons flow as they descend the stairs.

Leahy made observations of a variety of human phenomena as occupants descended the stairwells within two buildings included in this study (Buildings 4 and 5).[1] Leahy conducted an analysis on the platoon movement, passing behavior, and merging behavior within the evacuation drill of these two high-rise office buildings. Leahy defined a platoon as "a group of individuals who are spatially close from one person to the next and descend in the same approximate flow pattern" [29]. In distinguishing one platoon from the next Leady developed the following four categories:

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" [29].

The four categories which separate platoons were determined based upon a measurement of the exit time gap between occupants. The exit time for this data was determined as the point when one individual exits a particular camera view within a stairwell. Consequently, the exit time gap is defined as the difference in time between one individual exiting a camera view from the next.

In determining a spatial separation between platoons, Leahy decided that the total average exit time gap plus two standard deviations for the occupants of each stairwell separated each platoon. However, exit time gaps greater than 10 seconds were omitted from calculating the total average and averages were only taken where queuing was determined to have not

[1] See Chapter 3 for a description of Buildings 4 and 5.

occurred. This same method used by Leahy to determine the separation between platoons is also used in this thesis. However, this study accounts for events of queuing within the stairwells.

Leahy focused on platoon movement at two specific sections of stairwells 4A and 5A (described in Chapter 3). For Leahy's analysis on platoon movement, a steady flow of occupants was observed and the effects of queuing and merging were not present. Within in stairwell 4A, Leady observed "a flow of 177 occupants from the exit at the camera on floor 6 to the exit at the camera on floor 4" [29]. These occupants exited the landing on the 6th floor between 168.91 and 489.23 s after the fire alarm sounded [29]. During this time, no occupants entered the stairwell from the 4th or 5th floor, which excluded merging effects. Furthermore, no occupants passed each other during this analysis within stairwell 4A.

For stairwell 5A, Leahy observed "a flow of 181 individuals from the exit on floor 5 to the exit on floor 3" [29]. These occupants exited the landing on the 5th floor between 280.01 and 545.91 s after the alarm sounded [29]. Again, during this time no occupants entered the stairwell from the 3rd or 4th floor, which excluded merging effects. Also, in some cases, passing behavior was observed for the platoons in stairwell 5A.

Overall, Leahy identified 5 platoons within stairwell 4A and 13 platoons within stairwell 5A. Each platoon was analyzed to identify sub-platoons of individuals which travelled at different descent times within the overall platoon. Leahy concluded that platoons travelled in three distinct descent patterns: 1) elongation, 2) compression, and 3) equilibrium [29]. "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" [29]. The descent patterns of each platoon as well as if the platoons exhibited passing behavior in stairwell 5A are illustrated in Tables 2-4 and 2-5.

The results of the descent time patterns for the five platoons in stairwell 4A shown in Table 2-4 indicated that the platoons travelled in an alternating pattern between equilibrium and either compression or elongation. On the contrary, the descent time patterns of the platoons of stairwell 5A shown in Table 2-5 indicated that the majority of the platoons travelled in equilibrium. Also, the platoons of stairwell 5A displayed "an alternating trend between passing platoons and non-passing platoons" [29].

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 2-4: Descent Time Patterns of Platoons in Stair 4A [29]

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 2-5: Descent Time Pattern and Passing Behavior of Platoons in Stair 5A [29]

Hoskins' research focused on the individual behaviors and interactions between occupants in stairwells [30]. Hoskins defined platoons based upon a visual separation rather than the method of exit time gaps used by Leahy. Hoskins identified a separation of platoons as the number of steps or treads between one occupant and the next. If the two occupants were within three tread lengths of each other, they were in the same platoon. Therefore, if four or more tread lengths existed between two individuals, they were in separate platoons. In Hoskins research, rather than assume all evacuees behave in a uniform manner, such as the hydraulic model would suggest, he placed evacuees into different sets of flow units depending on how the occupants interacted with each other. For example, "if occupants were engaging in passing behavior, flow units were defined based on whether they were passing or being passed. If occupants were allowing individuals from the floor to enter into the stair, this created another set of flow units" [30].

Hoskins examined the interactions of occupants within 12 stairwells of Buildings 4, 5, 6, 7 and 8 (see Chapter 3). In determining how platoons formed within these 12 stairwells, Hoskins categorized each occupant within a platoon as a first person (leader) and a follower. This research of leaders and followers was similar to the research of Jones and Hewitt [12]. Overall, five different sets of flow units were developed by Hoskins depending on the actions of the first person. They are as follows:

1. First persons that engage in passing behavior
2. First persons that are being passed
3. First persons that are allowing others to enter the flow
4. First persons that experience congestion or a queue
5. First persons that are free to choose their own descent rate.

Therefore, Hoskins accounted for passing behaviors, merging behaviors, and queues. Hoskins observed platoons which passed others, were being passed, allowed a merge, experienced free flow, and/or experienced a queue.

Hoskins concluded that in most of the platoons observed, the leader set the pace for the descent rate and others followed. This occurred when slower leaders collected other occupants behind them because the occupants following the leader were originally walking faster than the leader. For these platoons, the occupants following did not pass the leader. Therefore, Hoskins noted that "the first persons (leaders) are influencing both the descent rate and the density" of the platoons [30].

2.6 Validity of Egress Data

Within the fire protection community, concerns have been raised to whether using the data from evacuation drills in high-rise buildings is acceptable for estimating actual egress times and how occupants will react with each other. Some individuals believe that because no actual fire or emergency is present during an evacuation drill, this data should not be used to make conclusions about people movement in fire incidents. However, in actual fire scenario within a high-rise building, the majority of the building population will not experience fire cues, such as smelling smoke or seeing the fire. The majority of the occupants will be located on the other floors above and below the fire floor and not come into contact with the fire once they are in the exit stairwell.

The building evacuation drills used in this study, with the exception of Building 6, had unannounced fire alarms. Therefore, each of the occupants did not know whether there was a fire or not. In one stairwell of both Building 4 and 5, firefighters travelled up past the occupants which could make some of the evacuees assume an actual fire scenario may have existed.

Moreover, research studies on evacuation drills and fire scenarios have shown that people will typically evacuate the same whether in an actual fire or not. Proulx stated that "the movement of people observed in normal building use and in evacuation drills is a good basis for predicting their movement in a fire emergency. Specifically, people should not be expected to react faster or move more efficiently in a fire emergency than they do normally" [31]. Proulx notes that evacuation drills and fire scenarios are "often a social response; people tend to act as a group and to attempt to evacuate with people with whom they have emotional ties" [31]. Therefore, the platoons analyzed in each building are likely to behave similar to those in an emergency scenario.

Chapter 3: Building Egress Data

The following chapter provides descriptions for the buildings used for this study as well as the egress data collected. Section 3.1 provides detailed descriptions of the four buildings and seven stairwells chosen for this study. Then, the type of data and the methods by which the data was collected is described in Section 3.2.

3.1 Building Descriptions

As of 2011, NIST collected data on people movement during high-rise stairwell evacuations from 13 residential and office buildings in the United States ranging from 6 to 62 stories in height [32]. Currently, egress data is available for 5 of the 13 buildings, namely Building 4, 5, 6, 7, and 8. This study contains an analysis of platoon movement in seven stairwells within Buildings 4, 5, 6, and 7. Each of these seven stairwells is chosen because of the differences in stairwell height, width, density and flow patterns. Table 3-1 provides an overview of the varying aspects of each building used in this study. Furthermore, an overview of the various aspects of the seven stairwells chosen including the number of occupants used for this study is provided in Table 3-2.

Building	Floors	Number of Stairwells Observed	Number of Occupants
4	24	2	605
5	10	2	804
6	62	4	607
7	18	4	1084

Table 3-1: Overview of Different Building Aspects

Stairwell	Stair Width (m)	Number of Occupants Observed	Number of Occupants Used	Number of Camera Views Used	Firefighter Counterflow
4A	1.12	249	239	11	Yes
4B	1.12	356	354	10	No
5A	1.27	436	432	5	No
5B	1.27	368	360	5	Yes
6_5	1.05	113	98	7	No
6_5A	1.05	156	148	6	No
7_3	1.12	292	292	7	No

Table 3-2: Overview of Different Stairwells Aspects

For each stairwell with the exception of stairwell 7_3, the number of occupants used in this study is less than the number observed. The observed occupants in Buildings 4, 5, and 6 which are excluded from this study are determined to be either safety officers who evacuated after all other occupants or occupants which entered the stairwell on one floor and exited on another floor which was not the exit floor. In either case, these excluded occupants do not reflect typical human movement during an evacuation; and therefore, are excluded for this analysis.

3.1.1 Building 4

Building 4 is a 24 story office building located on the west coast of the United States. There are two primary stairwells in Building 4, namely stairwell 4A and 4B. Both stairwells are 1.12 m wide and 1.02 m wide respectively between handrails [32]. Each step in both stairwells measure 0.18 m in height and 0.28 m in tread depth [32]. Stairwell 4A exits on the 2nd floor where the occupants must walk through the lobby to exit the building [32]. And stairwell 4B exits directly to the outside on the ground floor (floor 1) [32].

The evacuation drill of Building 4 was conducted by NIST in the spring of 2008 before lunch during normal business hours. A total of 605 occupants participated in the unannounced full building evacuation drill (249 in Stair 4A and 356 in Stair 4B) [32]. During the drill, counter-flow was present in stair 4A as three firefighters were sent up the stairwell approximately 90 seconds into the drill [32]. Furthermore, fire fighters were assigned to specific floors to conduct searches to ensure all occupants evacuated when the alarm sounded during the drill [32].

Prior to the evacuation drill, NIST set up 23 video cameras in the stairwells of Building 4 (11 in Stair 4A and 12 in Stair 4B). For stairwell 4A, cameras were positioned on every other floor starting on the exit floor (floor 2) and up to floor 22, giving camera views on floors 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, and 22. For stairwell 4B, a total of 12 cameras were placed on the exit floor (labeled P1) and on every other floor starting on floor 2 and up to floor 22. However, no data was analyzed by NIST on occupant movement on the cameras on floor 2 and floor 20. Therefore, data is only used for the cameras on floors P1, 4, 6, 8, 10, 12, 14, 16, 18, and 22.

The majority of the cameras in Building 4 show the main landing of the floor, as well as 2-3 steps leading to the landing and 3-4 steps leading away from the landing [32]. The view of each camera varied slightly due to some of the cameras being equipped with wide-angle lenses. A typical camera view seen by a wide-angle camera showing the main landing, as well as three steps leading to the landing and four steps leading away from the landing can be seen in Figure 3-1 [32].

Figure 3-1: Typical Camera View in Building 4 [32]

3.1.2 Building 5

Building 5 is a 10 story office building located on the west coast of the United States. There are two primary stairwells in Building 5, namely stairwell 5A and 5B. Both stairwells are 1.27 m wide and 1.22 m wide between handrails [32]. Each step in both stairwells measure 0.18 m in height and 0.28 m in tread depth [32]. Both stairwell 5A and 5B exit directly to the outside on the ground floor (floor 1) [32].

The evacuation drill of Building 5 was conducted by NIST in the spring of 2008 before lunch during normal business hours. A total of 804 occupants participated in the unannounced full building evacuation drill (436 in Stair 5A and 368 in Stair 5B) [32]. During the drill, counter-flow was present in stair 5B as six firefighters were sent up the stairwell to the 7th floor approximately 8 to 11 minutes into the drill [32]. Furthermore, fire fighters were assigned to specific floors to conduct searches to ensure all occupants evacuated when the alarm sounded during the drill [32].

Prior to the evacuation drill, NIST set up 10 video cameras in the stairwells of Building 5 (5 in Stair 5A and 5 in Stair 5B). For both stairwell 5A and 5B, cameras were positioned on every other floor starting on the exit floor (floor 1) and up to floor 9, giving camera views on floors 1, 3, 5, 7, and 9. The majority of the cameras in Building 5 show the main landing of the floor, as well as 3-4 steps leading to the landing and 4-6 steps leading away from the landing [32]. The view of each camera varied slightly due to some of the cameras being equipped with wide-angle lenses. A typical camera view seen by a wide-angle camera showing the main landing, as well as four steps leading to the landing and six steps leading away from the landing can be seen in Figure 3-2 [32].

Figure 3-2: Typical Camera View in Building 5 [32]

3.1.3 Building 6

Building 6 is 62 story office building located on the west coast of the United States. There are four primary stairwells in Building 6, namely stairwell 6_5, 6_5A, 6_6, and 6_6A. However, stairwell 6_6 and 6_6A share a common shaft and were not chosen for this study. Stairwell 6_5 and 6_5A are 1.05 m wide and the handrails do not extend into the stair width [32]. Each step in both stairwells measure 0.2 m in height and 0.254 m in tread depth [32]. Both stairwell 6_5 and 6_5A exit directly to the outside on the ground floor (floor 1) [32].

The evacuation drill of Building 6 was conducted by NIST in the spring of 2008 before lunch during normal business hours. A total of 269 occupants were observed in stairwell 6_5 and 6_5A during the full building evacuation drill (113 in Stair 6_5 and 156 in Stair 6_5A). At the time of the drill there were no occupants above floor 54 and participation in the evacuation drill voluntary. Both stairwell 6_5 and 6_5A have transfer corridors on various floors which directed the stair egress around mechanical spaces. Stairwell 6_5 has transfer corridors between floors 42 and 41, between 22 and 21, and on floor 4. And stairwell 6_5A has transfer corridors on floor 42, 22, and 4.

Prior to the evacuation drill, NIST set up 14 video cameras in stairwell 6_5 and 6_5A (8 in Stair 6_5 and 6 in Stair 6_5A). For stairwell 6_5, cameras were positioned on various floors starting on the exit floor (floor 1) and up to floor 51, giving camera views on floors 1, 7, 13, 20, 30, 36, 44, and 51. However, no occupants were observed by NIST on the camera at floor 51. For stairwell 6_5A, cameras were placed on various floors starting on the exit floor (floor 1) and up to floor 40, giving camera views of floors 1, 7, 12, 26, 34, and 40.

3.1.4 Building 7

Building 7 is an 18 story office building located on the east coast of the United States. There are a total of 12 exit stairwells located in Building 7; however, NIST only recorded occupant movement in four of the stairwells, namely stairwell 7_1, 7_3, 7_7, and 7_12. Only stairwell 7_3 was analyzed for this study. Stairwell 7_3 is 1.12 m wide and 0.91 m wide between handrails [32]. Each step in stairwell 7_3 measures 0.19 m in height and 0.25 m in tread depth [32]. Stairwell 7_3 exits on the 5th floor where the occupants must walk through the lobby to exit the building.

The evacuation drill of Building 7 was conducted by NIST in the spring of 2008 before lunch during normal business hours. A total of 292 occupants were observed in stairwell 7_3 in the unannounced full building evacuation drill. Prior to the evacuation drill, NIST set up 9 video cameras in stairwell 7_3 starting on the ground floor (floor 1) and up to floor 17. However, since the occupants exited on the 5th floor, data is given for the cameras on floors 5, 7, 9, 11, 13, 15, and 17. The majority of the cameras in building 7 show the main landing of the floor, as well as 2-3 steps leading to the landing and 3-4 steps leading away from the landing. A typical camera view in Building 7 showing the main landing, as well as two steps leading to the landing and three steps leading away from the landing can be seen in Figure 3-3 [32].

Figure 3-3: Typical Camera View in Building 7 [32]

3.2 Egress Data Collected

As previously mentioned, the use of video cameras on various floors within the stairwells allowed NIST to gather egress data for each occupant. A view of the main landing, as well as steps leading to and away from the landing was given by the overhead camera placement (Figures 3-1 to 3-3). This camera placement was essential for those at NIST to record when each occupant entered and exited the camera view for each particular floor.

Once the evacuation drills were completed for each building and the video footage was collected, NIST recorded data from each video into a spreadsheet format in Excel. For each stairwell, data was comprised of 1) each occupant evacuating in that stairwell and for 2) the time that occupant was seen at each specific floor (each camera position) [32]. For each stairwell in the evacuation drills, the data collected for each occupant includes the following: "occupant number, gender, floor of origin, whether he/she was carrying anything (Yes, No), his/her body size (less than ½ the stair, more than ½ the stair, or exactly half), whether he/she was alone or in a group during the drill, whether he/she was helping someone during the drill, and the floor on which he/she first seen" [32]. Furthermore, each time an occupant was seen on camera the following data was collected: "the time that he/she was seen entering the camera view, the time that he/she was seen leaving the camera view, his/her location on the stair (whether he/she was traveling on the inside, outside or the middle of the stair), and his/her handrail usage (whether he/she was using the inside or outside handrail, or both of them at the same time)" [32].

The occupant number assigned to each evacuee is based upon the order when they exited the stairwell. Therefore, occupant 1 was the first person to exit the stairwell, occupant 2 was the second to exit and so on. This numbering order is essential in determining if occupants pass each other when they are not seen on camera. For example, if occupant 3 is behind occupant 4 on floor 3, it can be determined that occupant 3 passed occupant 4 at some point before the exit floor.

For this data, each of the times recorded for each occupant as well as the alarm time are relative to the beginning of video recording for each specific location [32]. This is important in determining at what time each occupant enters the stairwell or specific camera view after the alarm has sounded. For example, if the building wide alarm sounded at 5 minutes and 0 seconds and occupant 1 enters the stairwell at 6 minutes and 30 seconds, then occupant 1 has entered approximately a minute and a half into the drill.

Also for this data, the distance between occupants within a camera view was also determined at NIST by viewing the number of tread lengths between occupants. This value was recorded as an occupant being 1, 2, or 3 treads behind the previous occupant. Any distance greater than 3 tread lengths was not noted in the spreadsheets. These values are important in determining the proximity of occupants as well as when queues occurred in the stairwells.

For this study, the data involving the occupant's body size, if the occupant was carrying anything, if the occupant was helping someone and the occupant's handrail usage are not utilized. However, the enter and exit times of each camera view for all of the occupants are used extensively in identifying each of the platoons as well as the calculation of descent times as seen in Chapter 4.

Chapter 4: Data Analysis

Chapter 4 provides an explanation of how the egress data produced by NIST [32] is used to calculate descent times of occupants, determine where queues occurred, and identify platoons. For this analysis, the enter and exit camera times in each stairwell for each occupant is synchronized with respect to the time when the alarm sounds. This is the same procedure used by Leahy [29] in his analysis of platoons. This method is conducted by subtracting each enter and exit time from the time when the alarm sounded on that particular floor, giving a time of t=0 for when the building wide alarm sounded. All times used in this research are given with respect to when the alarm sounded.

4.1 Calculation of Descent Times

A local descent time for every occupant is calculated using the exit times from one camera view to the next camera view. An example of the exit point for a camera view in building 4 is indicated by the solid red line shown in Figure 4-1. The exit point for every camera view is simply where the occupant is last seen on camera. A local descent time can be calculated by subtracting the exit time from the camera on one floor from the exit time of the camera on the previous floor above. For example, if an occupant exits the camera view on floor 7 at 10 seconds and exits the camera view on floor 5 at 30 seconds, then the occupant's descent time from floor 7 to floor 5 is simply:

$$\mathrm{t}_{7-5} = 30\ \mathrm{s} - 10\ \mathrm{s} = 20\ \mathrm{s}$$

These local descent times are used in the analysis of the descent of the platoons in Chapter 5.

Figure 4-1: Exit Point for a Camera View in Building 4

4.2 Data Involving Queues

The egress data collected by NIST is publically available in spreadsheets (see Chapter 3). However, the videos used to capture these data are not available to the public. Therefore, one specific technique was used to determine when a queue occurred within the stairwell. A queue is determined to have occurred either when the flow of occupants comes to a stop or when there is a significant slowing of occupants within a stairwell. Queues occurred at multiple floors in the stairwells of Buildings 4, 5, and 7.

Some researchers [9, 11] have speculated that queues form in stairwells due to a merging of occupants coming down the stairs and occupants coming onto the stairs at the same floor landing. These queues may have formed as a result of the stop-and-go phenomenon where evacuees in the stairwell are stopping to let others from the floor enter as noted by Pauls [9]. In other cases the queues may have formed simply due to a high volume of occupants in the stairwell. The queues occurring in Buildings 4, 5, and 7 significantly impacted the descent times of the platoons, which is shown in Chapter 5.

In order to determine where the queues occurred within the stairwells, plots of the time each occupant spent on camera and off camera were used. These plots clearly indicated which occupants either stopped or slowed their descent. Camera view times were calculated for every occupant by subtracting their exit time minus their enter time at each camera view. It is assumed that when there is an upward spike in either the camera view time or off camera time, the particular occupant(s) experienced either a stoppage or a slowing of movement caused by a queue. An example of an upward spike in camera view time is shown in Figure 4-2 for the camera at floor 14 in stairwell 4A.

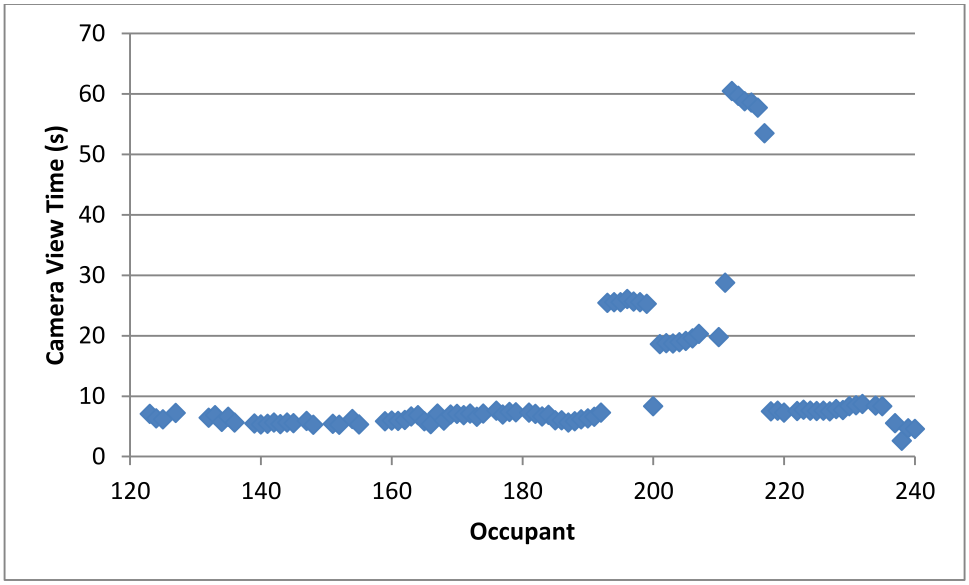

Figure 4-2: Stair 4A, Floor 14 Camera View Time vs. Occupant

Figure 4-2 clearly indicates an upward spike the camera view times for occupants 193 to 217, with the exception of occupant 200.[2] The camera view time for occupants 193 to 211 was on the order of 20 to 30 seconds. Also, the camera view time for occupants 212 to 217 was on the order of 55 to 60 seconds. However, before and after the upward spike, the average camera view time for the other occupants was about 6.5 seconds. This clearly indicates that a queue has occurred from occupants 193 to 217 as their camera view times were more than triple the

[2] Occupant 200 entered the camera view 19.52 seconds after occupant 199; however, the queue slightly dissipated at this point allowing occupant 200 to exit the camera in 8.34 seconds.

average time. Plots of the camera view time vs. occupant for each of the seven stairwells of Buildings 4, 5, 6, and 7 are included in Appendix A.[3]

Along with the camera view times, time spent off camera between each of the camera views was plotted to determine where queues occurred in the stairwells. Similar to the camera view times, an upward spike in the off camera time indicates either that the occupants either slowed their descent or came to a stop. Off camera times were simply calculated by subtracting an occupant's enter time on one camera minus the exit time from the last camera above. Figure 4-3 depicts the off camera times for occupants between the camera views at floor 14 and floor 12 in stairwell 4A.

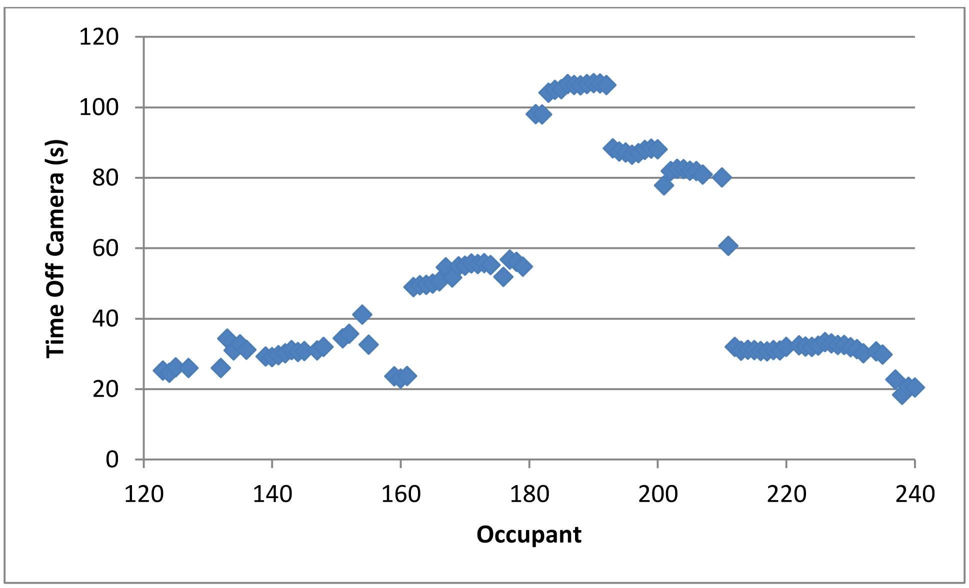

Figure 4-3: Stair 4A, Floor 14 to 12 Time Off Camera vs. Occupant

Once again, an upward spike in the data can be seen for occupants 181 to 210. The time off camera for these occupants was on the order of 80 to 110 seconds. However, the average

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[3] Some of the camera view times are excluded for occupants that were safety officers or those that took breaks on the floor landing. For example, in stairwell 4B at floor 8, occupants 351 and 352 enter the stairwell at 183.21 and 186.32 seconds after the alarm sounded and exited at 335.27 and 334. 56 seconds respectively. Each of these occupants spent about 150 seconds in the camera view. In the spreadsheets occupant 352 is recorded as wearing an orange emergency vest which clearly indicates that this occupant is a safety officer. These data points were clear outliers and do not reflect typical occupant movement during the evacuation.

time off camera for occupants 123 to 179 and occupants 182 to 240 was about 40 seconds and 30 seconds respectively. This indicates that a queue has formed between the cameras at floor 14 and floor 12 since the time off camera for occupants 181 to 210 is a little more than double the time off camera of the other occupants. Again, plots of the time off camera for the occupants of the seven stairwells in Buildings 4, 5, 6, and 7 are included in Appendix A.

In comparing Figure 4-2 and 4-3, the times are greater for the off camera than the time on camera. This is expected since the majority of the time the occupants are not seen during the evacuation drills. Also, in Figure 4-2 occupants 193 to 217 were affected by the queue and in Figure 4-3 occupants 181 to 210 were affected by the queue. The difference in these occupants is dependent upon their position in the stairwell. Occupants 181 to 210 were affected below the camera at floor 14 and occupants 193 to 217 were affected at the camera at floor 14. Therefore, Figures 4-2 and 4-3 show how the queue propagated up stairwell 4A. It is important to understand where queues occur and how they affect the descent rates of platoons for this thesis. Therefore, the platoon analysis for this research is more macroscopic than that of Leahy [29] since his analysis of platoons was under conditions where queues did not occur.

4.3 Platoon Identification and Assumptions

As previously mentioned, a platoon is defined as a group of individuals that are spatially close to each other. Therefore, platoons are spatially separated from one another. However, the main assumption for the analysis of platoons is that each platoon will display a different flow pattern (i.e. different patterns in descent times). These different flow patterns were identified by Leahy [29] and are identified as platoon elongation, compression, and equilibrium. Platoon elongation occurs when the descent times between individuals within a platoon increase from one person to the next. This is indicated by a positively increasing linear trend in the descent time of a platoon. Likewise, platoon compression occurs when the descent times between individuals within a platoon decrease from one person to the next. This is indicated by a negatively decreasing linear trend in the descent time of a platoon. Finally, platoon equilibrium occurs when the descent times for the occupants within a platoon remain the same. For this analysis, the identification methods of platoons are as follows:

1. A platoon is spatially separated from the other platoons.
2. A platoon that is continuously passing other occupants or continuously being passed by other occupants is separated.
3. One-person platoons are separated.

The measurement on the spatial separation between platoons was determined from the exit time gap between individuals and is explained in section 4.3.1. The time that each occupant entered the camera view was not used for this measurement because the enter points were not the same for all occupants since some entered the stairwell on the floors which cameras were placed. An example of two different exit points is illustrated in Figure 4-4 showing a typical camera view within building 4. In this figure, the dashed yellow line indicates the enter point for the occupants entering the stairwell on that floor. Furthermore, the solid white line indicates the enter point for the occupants descending the stairwell from the floors above.

Figure 4-4: Enter Points of Floor (Dashed Yellow) and Stair Occupants (Solid White)

In many instances for this data, passing occurs among individuals within a stairwell. In most cases, one or more occupants may pass one or more occupants within the same platoon. Also, some cases exist where two occupants in a platoon descend the stairs shoulder-to-shoulder and appear to slightly pass each other at different camera views. For this research, it was determined that if one or more occupants were passing others or being passed by others over two or more camera views, then they are considered to be a separate platoon. Also, if one or more occupants clearly stop their descent indicated by a spike on the plots presented in Chapter 5, then these one or more occupants are considered to be a separate platoon. This determination is slightly different than that of Leahy [29] since his research separated platoons which were passed or passing others between camera views even if the occupants did not stop during their descent. However, his research was only conducted between two camera views in two different stairwells which was microscopic in nature.

Finally, one-person platoons exist in one of two scenarios. For example, a one-person platoon exists when an individual is spatially separated from the other platoons and descends the stairs alone. Also, a one-person platoon exists when an occupant is continuously being passed by others or is being passed by others over the course of two or more camera views.

4.3.1 Exit Time Gaps

In order to measure the spatial separation between platoons, the same method was used in this analysis as was conducted by Leahy [29]. Each of the occupants viewed on camera at each floor within the stairwells was placed in order from the first to exit the camera to the last to exit the camera. Once the occupants were placed in order, the exit time gap was calculated by subtracting the exit time of one occupant minus the exit time of the occupant just ahead. For example, if the first occupant exits the camera view at floor 2 at 15 seconds and second occupant exits the camera view at floor 2 at 19 seconds, then the exit time gap for the second occupant is 4 seconds.

The average exit time gap with standard deviations from one occupant to the next is illustrated in Table 4-1 for each stairwell. In this analysis, it was determined that exit time gaps greater than 10 seconds may indicate that a queue has occurred when one person exits the camera view and the next takes 10 or more seconds to exit due to a decrease in the flow. Or an exit time gap greater than 10 seconds may indicate a large spatial separate between occupants where no flow is occurring in the camera view. In either case, exit time gaps greater than 10 seconds were omitted from calculating the average exit time gap and standard deviation for all stairs.

Stairwell	Average Exit Time Gap in Seconds (Standard Deviation)	Average Exit Time Gap Plus Two Standard Deviations in Seconds
4A	1.94 (1.00)	3.94
4B	1.86 (1.03)	3.92
5A	1.45 (0.91)	3.27
5B	1.66 (1.12)	3.90
6_5	2.51 (1.75)	6.01
6_5A	2.16 (1.47)	5.10
7_3	2.06 (1.34)	4.74

Table 4-1: Average Exit Time Gaps with Standard Deviations

By Leahy's [29] criterion the average exit time gap plus two standard deviations for each stairwell classifies a spatial separation from one platoon to the next. This determination was made by a statistical rule that a value greater than two standard deviations from the average is statistically significant at the 95% confidence interval. Therefore, occupants exiting a camera view more than two standard deviations from the average can be considered to be statistically significant and adequately spaced. The average exit time gap plus two standard deviations are also included in Table 4-1 for each stairwell. Also, the frequency distributions of the data points for the exit time gaps shown in Table 4-1 are presented in Figure 4-5.

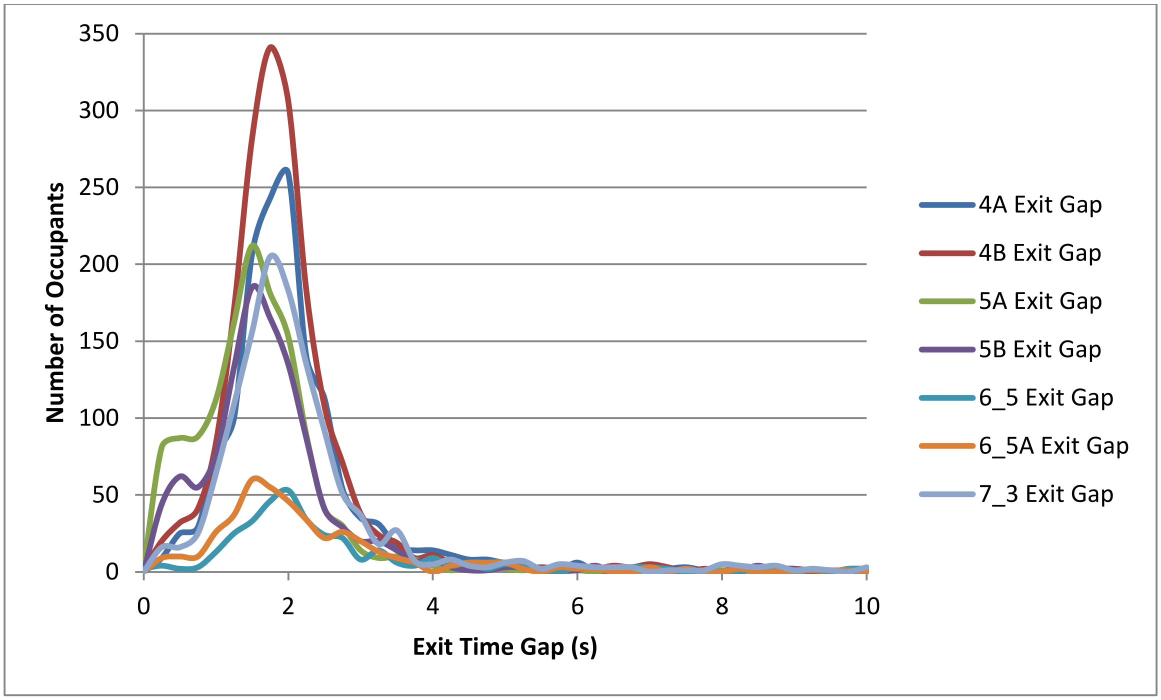


Figure 4-5: Frequency Distribution of Exit Time Gaps for Each Stairwell

4.3.2 Number of Treads Behind

A tread separation analysis was conducted by Hoskins [30] and used in his analysis of platoons as previously mentioned in section 2.5. Hoskins identified the number of treads between occupants indicated by a value of 1, 2, or 3 treads. If the cell was left empty, this indicated that the number of treads between occupants was 4 or more. Each "tread" corresponds to the tread length of a step in each stairwell and was estimated by viewing the occupants in each camera view.

In the event that an exit time gap was greater than the average plus two standard deviations, the number of treads between occupants was viewed to determine the proximity of the two occupants. If the number of treads between the occupants was 3 or less, then the two occupants were considered to be in the same platoon. For example, if an occupant in stairwell 5A exited a camera view at 10 seconds and the next occupant exited the same camera view at 20 seconds but was listed as being 2 treads behind the first occupant, then these two occupants were considered to be in the same platoon even though the exit time gap was greater than 3.27 seconds. In every circumstance when two occupants were within 3 treads of each other, but the exit time gap was greater than the average plus two standard deviations, a queue was determined to have occurred.

4.4 Platoon Analysis

The primary purpose of this research was to understand what happens to platoons during the entire descent of a high-rise stairwell. Platoons identified in a stairwell on the highest levels of a building may have increased, decreased, or remained cohesive in size. Conversely, platoons identified in a high-rise stairwell on a lower level close to the exit floor may not have experienced many changes during their short descent. Therefore in this analysis, platoons are only identified for the upper half of the camera views associated for each stairwell. For example, if a stairwell contained 10 camera views, then platoons are identified for the highest 5 camera views. In the event that a stairwell contained an odd number of camera views, then platoons are identified for the upper half of the camera views plus the next one down. For example, if a stairwell contained 11 camera views, then platoons are identified for the highest 6 camera views.

As previously mentioned, as a platoon descended a stairwell from one camera view to the next, its size either increased, decreased, or remained unchanged. A platoon's size increased by either adding new occupants to the platoon or merging with one or more other platoons. A platoon's size decreased only by undergoing fragmentation when one or more occupants split apart from the platoon. Once the identified platoons reached the lower half of the camera views, the new occupants entering the stairwell on these floors could only be added to the previously identified platoons. All other occupants entering the floors for the lower half of the camera views that did not merge with a previously identified platoon were discarded for this analysis.

In order to visualize how the platoons descended each of the stairwells, flowcharts were created which indicated a platoon's size and whether the platoon fragmented, merged, or remained unchanged. An explanation of how these flowcharts were created is illustrated in Figure 4-6. Platoon flowcharts for all seven stairwells are included in Appendix B.

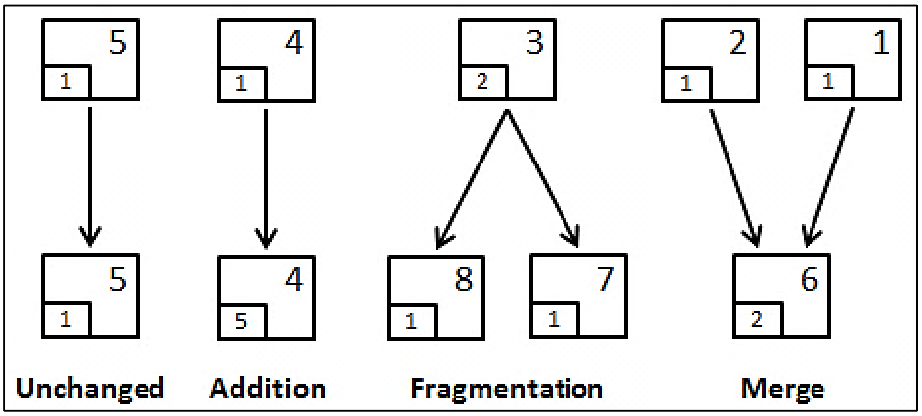


Figure 4-6: Platoon Flowchart Analysis

In Figure 4-6, each large box indicates a separate platoon with the associated platoon's number in the upper right corner. Also, the small box in the bottom left corner of each large box indicates the size of the platoon. In this figure, platoon 5 represents an unchanged platoon as it remains the same size. Platoon 4 has changed by adding 4 new occupants but retains the same platoon number. Platoon 3 fragments creating platoons 7 and 8. Finally, platoons 1 and 2 merge creating platoon 6.

Chapter 5: Results and Discussion

The following chapter provides a detailed analysis of the platoons identified in the seven stairwells analyzed from the evacuation data collected in Buildings 4, 5, 6, and 7. Each of the occupants is numbered starting with the first to exit a particular camera view. Also, all of the platoons for every stairwell are numbered in order starting with the last platoon to exit the camera view at the highest level in the stairwell. Therefore, platoon 1 will be the last platoon viewed exiting the camera on the highest floor level.

As a platoon descends the stairwell, the assigned number to the platoon will remain the same as long as the platoon remains unchanged or adds new occupants. Therefore, if a platoon undergoes fragmentation and/or merges with one or more other platoons, then a new number is assigned starting with the last platoon to undergo a change at each particular camera view. All of the associated changes for every platoon are described in Sections 5.1 to 5.4. Section 5.5 contains an analysis of the size and variations for all of the platoons analyzed. Finally, a qualitative analysis of platoons identified in the Pathfinder computer egress model is described in Section 5.6.

5.1 Platoon Analysis of Building 4

The following section contains an analysis of the platoons identified in Building 4 using the methodology described in Sections 4.3 and 4.4. All of the changes in the descent of the platoons for Building 4 are described in Section 5.1.3. Each of the two stairwells in building 4 is identical with the exception that firefighter counterflow is present in stairwell 4A.

5.1.1 Stairwell 4A

A total of 6 platoons are identified exiting the camera view at floor 22 of stairwell 4A based on the exit time gap. Figure 5-1 illustrates the descent times of the platoons from floor 22 to 20. Platoons 1 and 6 travel to floor 20 in equilibrium and platoon 4 elongates.

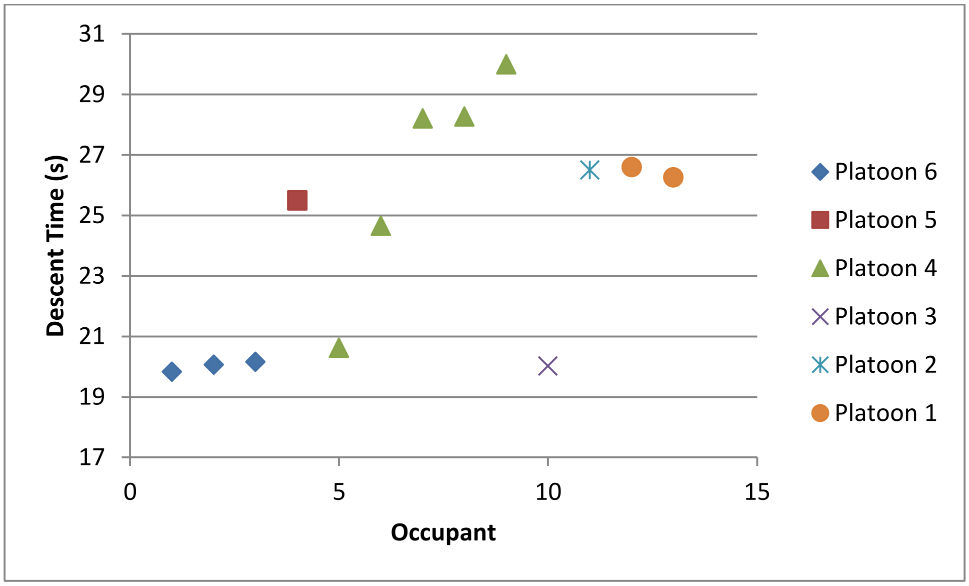


Figure 5-1: Stairwell 4A Platoon Descent Times from Floor 22 to 20

A plot of the descent times for the platoons as they travel from floor 20 to 18 is shown in Figure 5-2. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 20:

- Platoons 1, 2, and 3 remain unchanged.
- New occupants are added to platoons 5 and 6.
- Platoon 4 fragments creating platoons 8 and 9.
- Four new platoons emerge, platoons 7, 10, 11, and 12.

With the exception of the 4 one-person platoons and platoons 7 and 9, the other platoons descend the two floors in equilibrium. Conversely, platoons 7 and 9 elongate during the descent from floor 20 to 18.

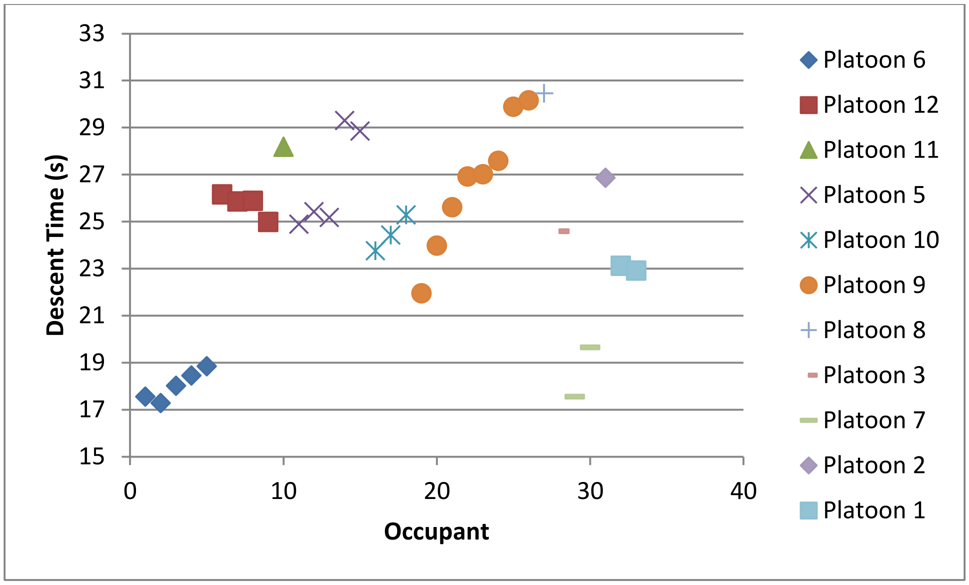


Figure 5-2: Stairwell 4A Platoon Descent Times from Floor 20 to 18

The platoon descent times from floor 18 to 16 are illustrated in Figure 5-3. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 18:

- Platoons 1, 2, and 10 remain unchanged.
- New occupants are added to platoons 6 and 12.
- Platoons 3 and 8 merge together creating platoon 15.
- Platoons 5 and 11 merge together and added new occupants creating platoon 20.
- Platoon 7 fragments creating platoons 13 and 14.
- Platoon 9 fragments creating platoons 16, 17, 18, and 19.
- One new platoon emerges, platoon 21.

Overall, during the descent from floor 18 to 16, platoons 6 and 12 elongate and platoons 10 and 18 travel in compression. All of the other platoons travel in equilibrium.

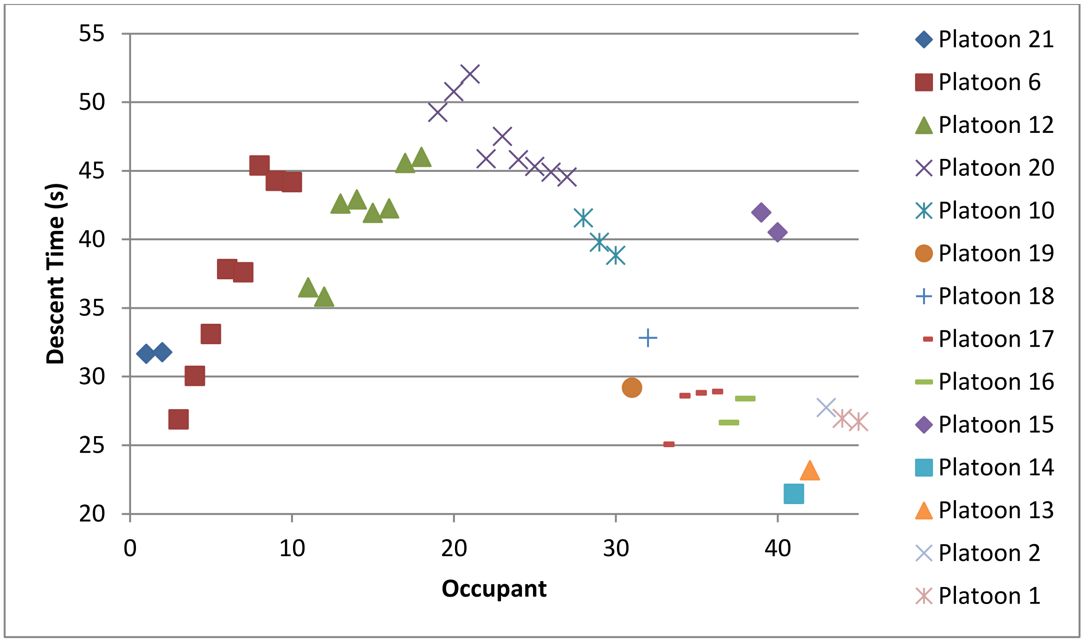


Figure 5-3: Stairwell 4A Platoon Descent Times from Floor 18 to 16

The descent times of the platoons from floor 16 to 14 are shown in Figure 5-4. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 16:

- Platoons 1, 2, and 13 remain unchanged.
- New occupants are added to platoon 21.
- Platoon 14 and 15 merge together and add one new occupant creating platoon 24.
- Platoons 16, 17, and 18 merge together creating platoon 25.
- Platoons 6, 10, 12, 19, and 20 merge together creating platoon 26.
- Four new platoons emerge during this descent, platoons 22, 23, 27 and 28.

Overall, during the descent from floor 16 to 14, every platoon travels in equilibrium with the exception of platoon 26, which travels in compression. Sub-platoons are evident in platoon 26 indicated by the small clusters of occupants with similar descent times. These sub-platoons are similar to the ones analyzed by Leahy [29] with the exception that the sub-platoons analyzed in his research were under non-queued conditions. A queue occurs during this descent indicated by the descent times more than tripling for the last sub-platoon of platoon 26 compared to the first.

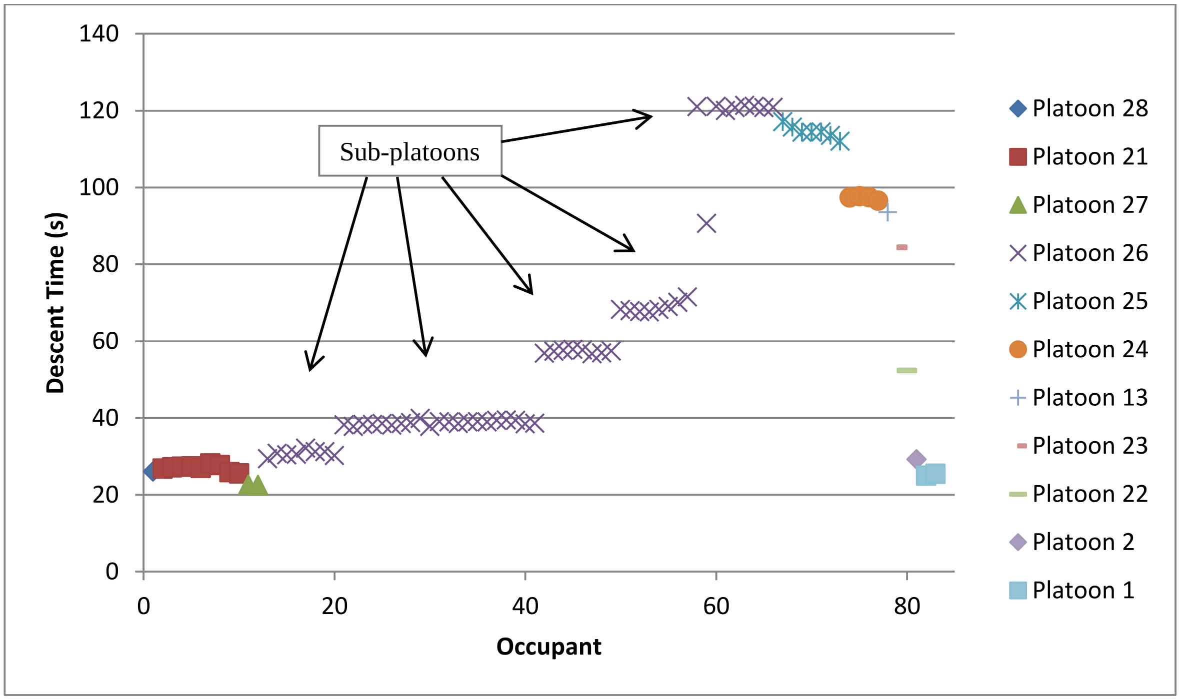


Figure 5-4: Stairwell 4A Platoon Descent Times from Floor 16 to 14

Figure 5-5 illustrates the descent times for the platoons from floor 14 to 12. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 14:

- Platoons 1 and 2 remain unchanged.
- Platoons 13, 22, 23, 24, 25, 26 merge together creating platoon 30.
- New occupants are added to platoons 28 and 30.
- Platoons 21 and 27 merge together creating platoon 32.
- Three new platoons emerge, platoons 29, 31, and 33.

Sub-platoons are present in platoons 30 and 32 during this descent. Also, a queue is again present indicated by the large descent times in platoon 30. This queue was partly caused by counterflow as 3 firefighters were seen passing occupants 33 and 34 in the camera view at floor 12. The descent time from occupant 33 to 34 increased from 68.4 to 107.3 seconds as a result of the counterflow.

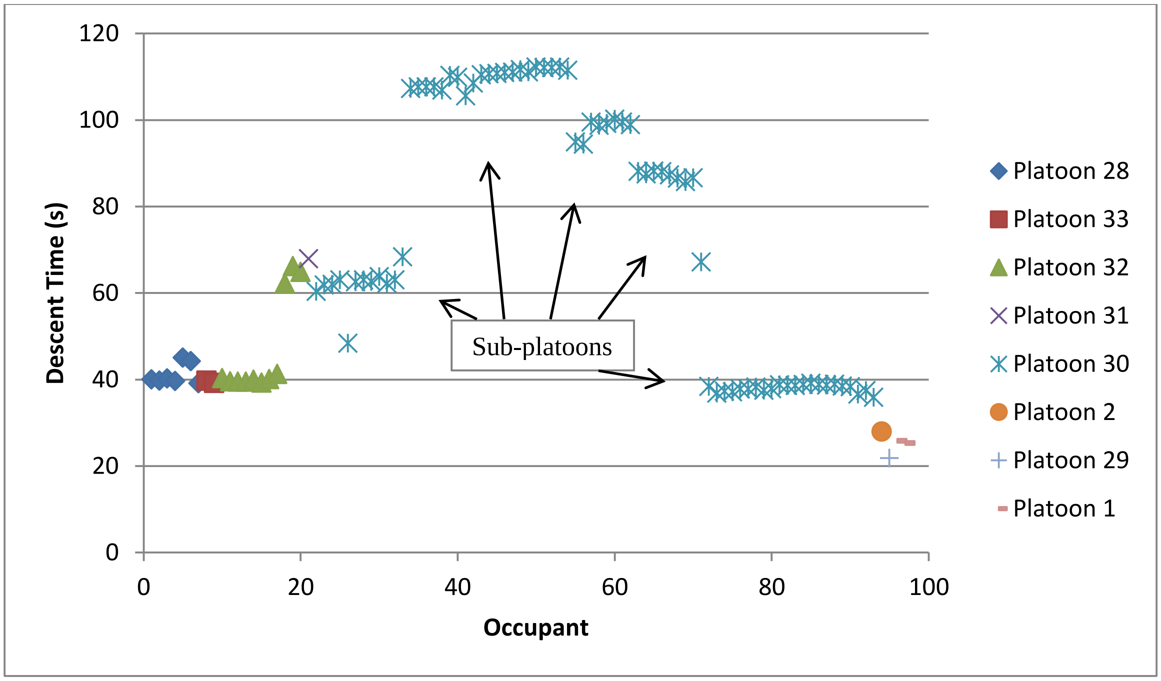


Figure 5-5: Stairwell 4A Platoon Descent Times from Floor 14 to 12

A plot of the descent times of the platoons from floor 12 to 10 is illustrated in Figure 5-6. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 12:

- Platoons 1, 2, and 29 remain unchanged.
- Platoon 30 fragments creating platoons 34 and 35.
- Platoons 28, 31, 32, and 33 merge together with platoon 35 and add new occupants.
- One new platoon emerges, platoon 36.

Sub-platoons again exist during this descent in platoon 35. Also, a queue again exists indicated by the increase in the descent times in platoon 35. This queue was again partly caused by counterflow as the 3 firefighters passed occupants 32 and 33 at the camera view at floor 10. The descent times increased from 67 to 107.5 seconds for these two occupants. At this point, the upper half of the camera views in stairwell 4A have been analyzed; therefore, no new platoons will be analyzed for the lower half.

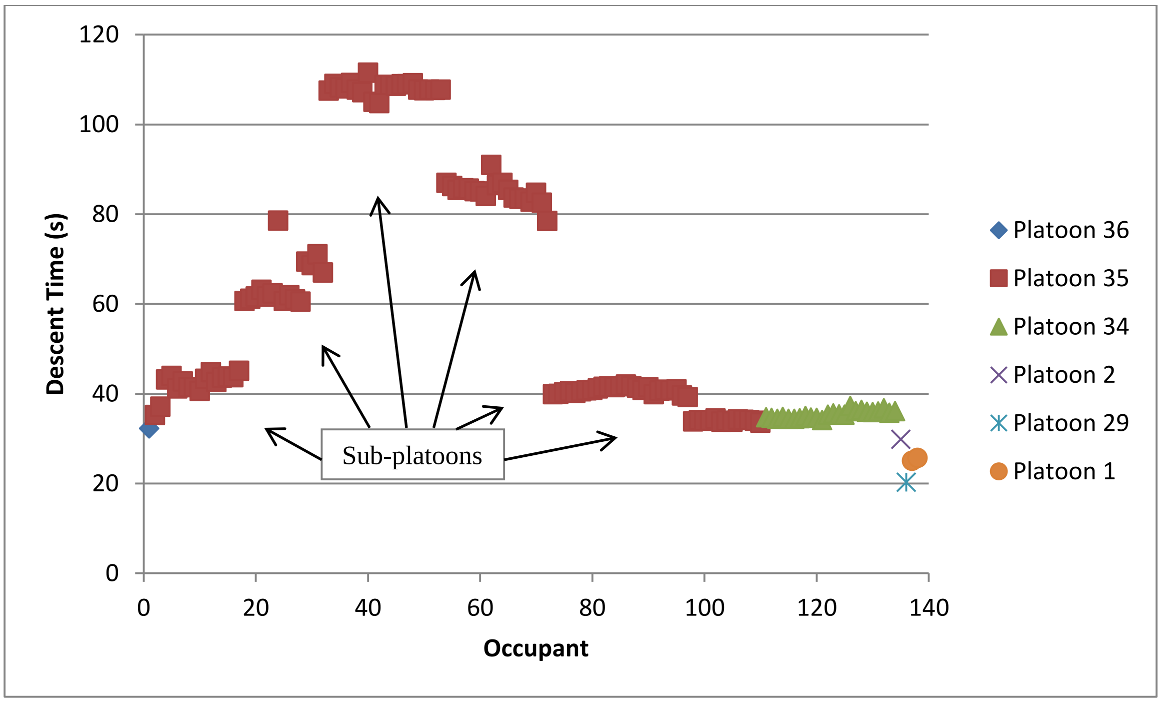


Figure 5-6: Stairwell 4A Platoon Descent Times from Floor 12 to 10

Figure 5-7 illustrates the descent times for the platoons from floor 10 to 8. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 10:

- Platoons 1, 2, and 29 remain unchanged.
- Platoon 34 adds one new occupant.
- Platoon 35 fragments creating platoons 37 and 38, both of which add new occupants.
- Platoon 36 merges with platoon 38.

Sub-platoons are again present during this descent in platoon 38. Also, a queue again has occurred partly caused by the 3 firefighters that passed occupants 30 and 31 at the camera view at floor 8. This led to an increase in the descent times from 71.3 to 81.2 seconds.

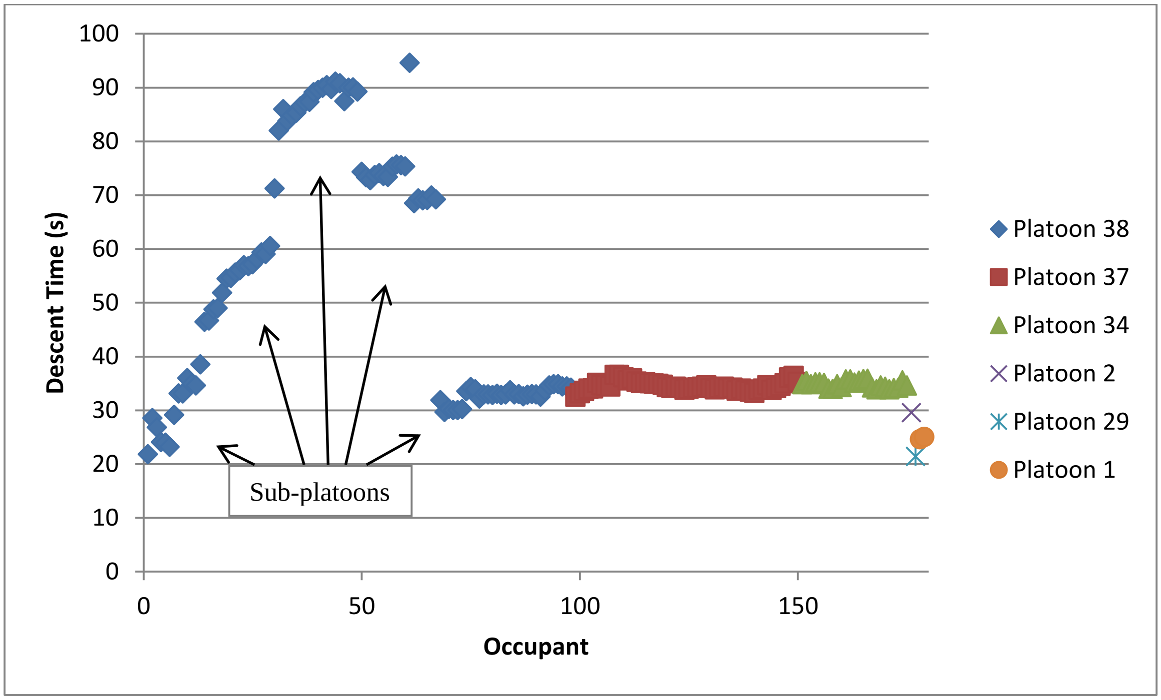


Figure 5-7: Stairwell 4A Platoon Descent Times from Floor 10 to 8

A plot of the descent times for the platoons from floor 8 to 6 is shown in Figure 5-8. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 8:

- Platoons 1, 2, and 29 remain unchanged.
- Platoons 34, 37, and 38 fragment.
- Occupants from platoons 34 and 37 merge to form platoon 40.
- Occupants from platoons 37 and 38 merge to form platoon 41.
- Platoons 41 and 42 add new occupants.

During this descent, the queue from the previous descent plots appears to be dissipating as the descent times slightly increase in platoon 41. Counterflow was also present during this descent as the firefighters passed occupants 17-20 at the camera view on floor 6. However, the descent times increased by only 7 seconds between these occupants.

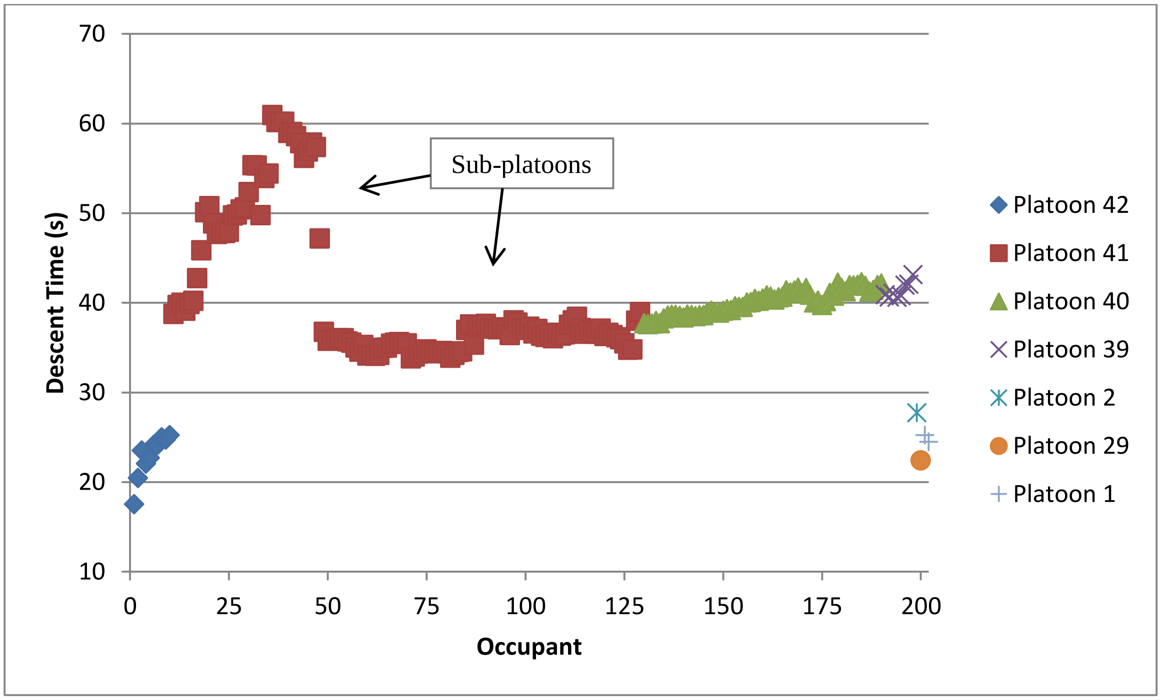


Figure 5-8: Stairwell 4A Platoon Descent Times from Floor 8 to 6

Figure 5-9 illustrates the descent times for the platoons from floor 6 to 4. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 6:

- Platoons 1, 2, and 29 remain unchanged.
- Platoons 41 and 42 add new occupants.
- Platoons 39 and 40 merge together creating platoon 43.

The presence of counterflow was again present during this descent as the 3 firefighters passed occupants 4 and 5 at the camera view at floor 4. A slight increase of 9.5 seconds was caused by this counterflow.

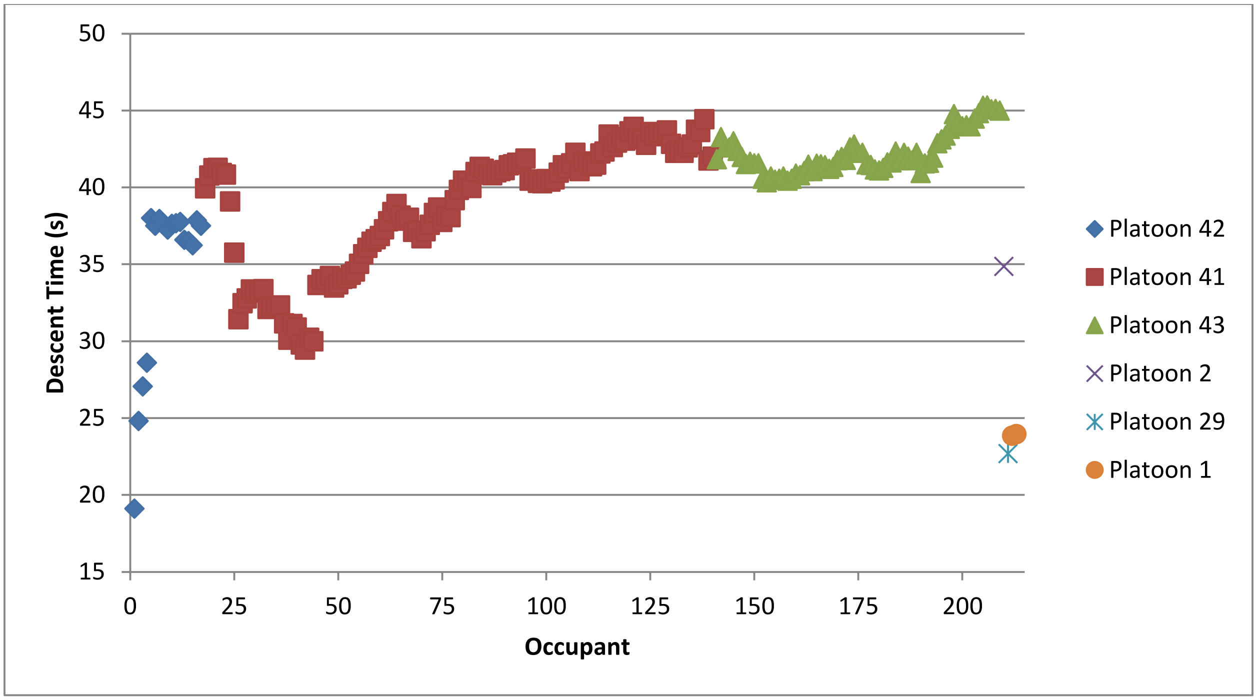


Figure 5-9: Stairwell 4A Platoon Descent Times from Floor 6 to 4

The final descent for the platoons from floor 4 to 2 is illustrated in Figure 5-10. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 4:

- During this descent platoons 1, 2, 29, and 43 remain unchanged.
- Platoon 41 fragments creating platoons 44, 45, and 46.
- Platoon 42 fragments creating platoons 47 and 48, both of which add new occupants.

Similar to the previous descent plot, queuing is not present in the descent of the platoons from floors 4 to 2. This is indicated by the steady trend in the descent times remaining around 40 seconds. During this descent, platoons 41 and 42 elongate while all other platoons travel in equilibrium.

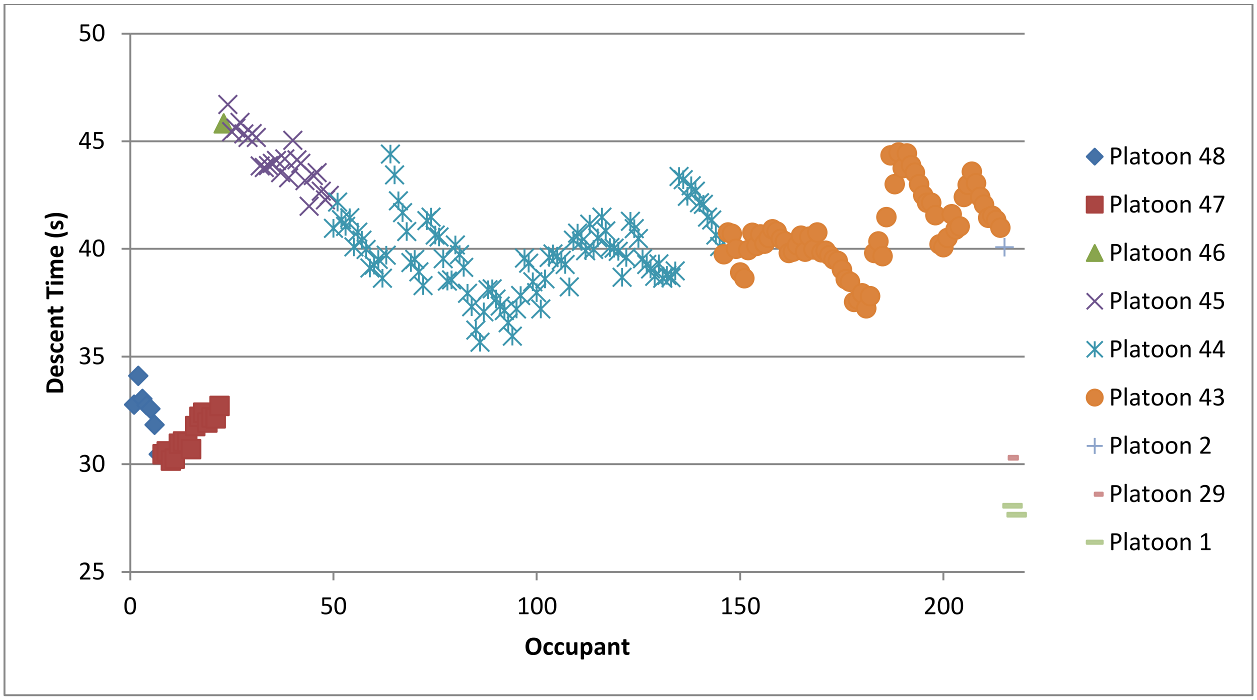


Figure 5-10: Stairwell 4A Platoon Descent Times from Floor 4 to 2

5.1.2 Stairwell 4B

A total of 12 platoons are identified exiting the camera view at floor 22. Figure 5-11 illustrates the descent times of the platoons from floor 22 to 18. Platoons 2, 4, 10, and 12 are one-person platoons. Each of the other platoons travel in equilibrium with the exception of platoon 8 which elongates.

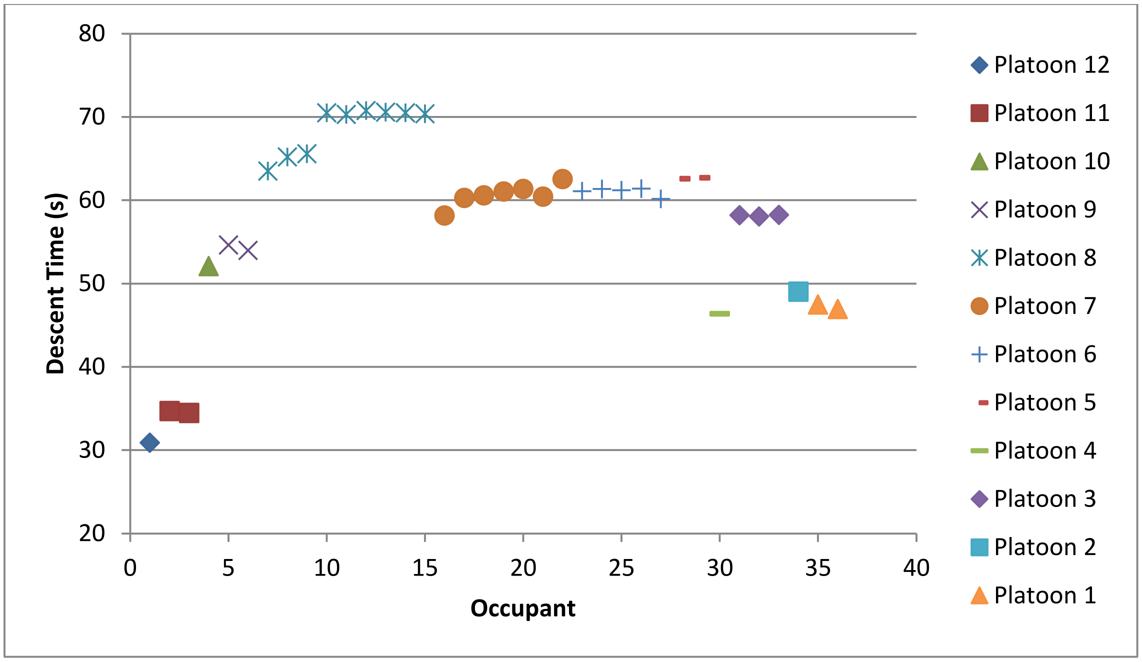


Figure 5-11: Stairwell 4B Platoon Descent Times from Floor 22 to 18

Figure 5-12 illustrates the descent times of the platoons from floor 18 to 16. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 18:

- Platoons 1, 2, 3, 4, 5, and 12 remain unchanged.
- Platoons 6, 7, 8, 9, and 10 all merge together and add new occupants creating platoon 16.
- Platoon 11 adds new occupants.
- Five new platoons emerge, platoons 13, 14, 15, 17, and 18.

During this descent sub-platoons are again present, similar to the sub-platoons in stairwell 4A. A queue has formed during this descent indicated by the descent times more than doubling in Platoon 16. Also, this queue creates two sub-platoons indicated by the spike in the decent times of the last nine occupants. Overall, all of the platoons travel in equilibrium with the exception of the last sub-platoon in platoon 16, which elongates.

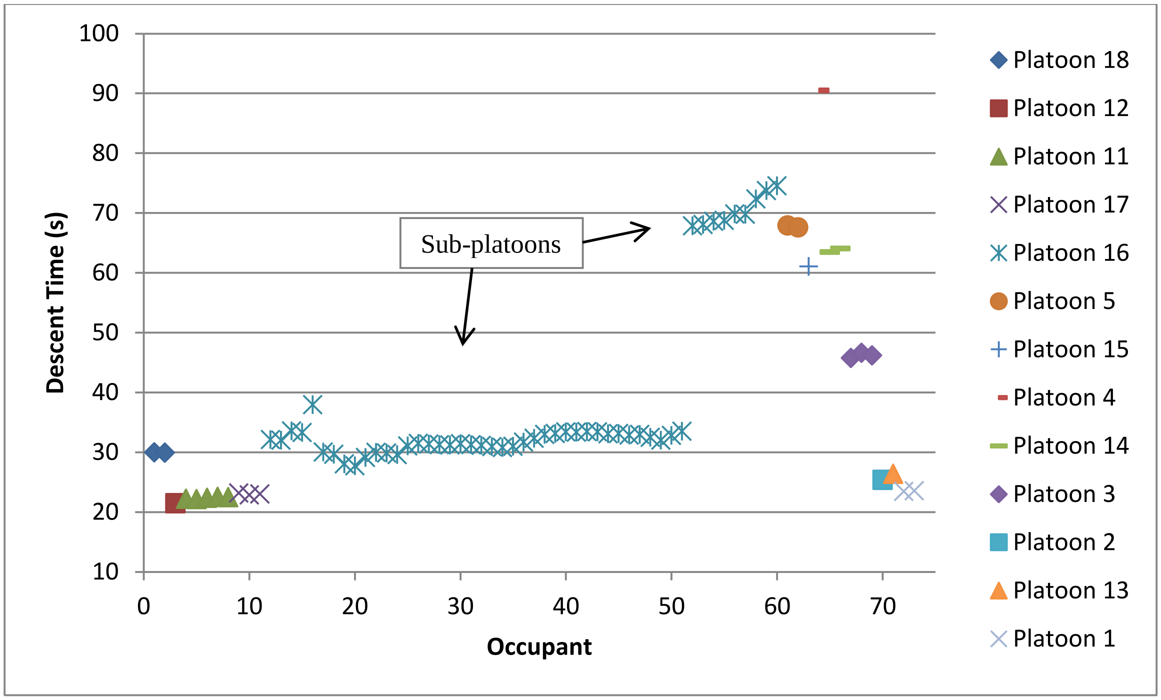


Figure 5-12: Stairwell 4B Platoon Descent Times from Floor 18 to 16

Figure 5-13 illustrates the descent times of the platoons from floor 16 to 14. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 16:

- Platoons 1, 2, 13, and 17 remain unchanged.
- Platoons 3, 4, 5, 14, 15, and 16 merge together and add new occupants creating platoon 19.
- Platoon 11 adds new occupants.
- Platoons 12 and 18 merged together and add new occupants creating platoon 22.
- Three new platoons emerge, platoons 20, 21, and 23.

A queue is again present during the descent of these two floors indicated by the spike in the descent times in platoon 19. Also, six distinct sub-platoons are present in platoon 19. The first two sub-platoons elongate and the last four travel in equilibrium.

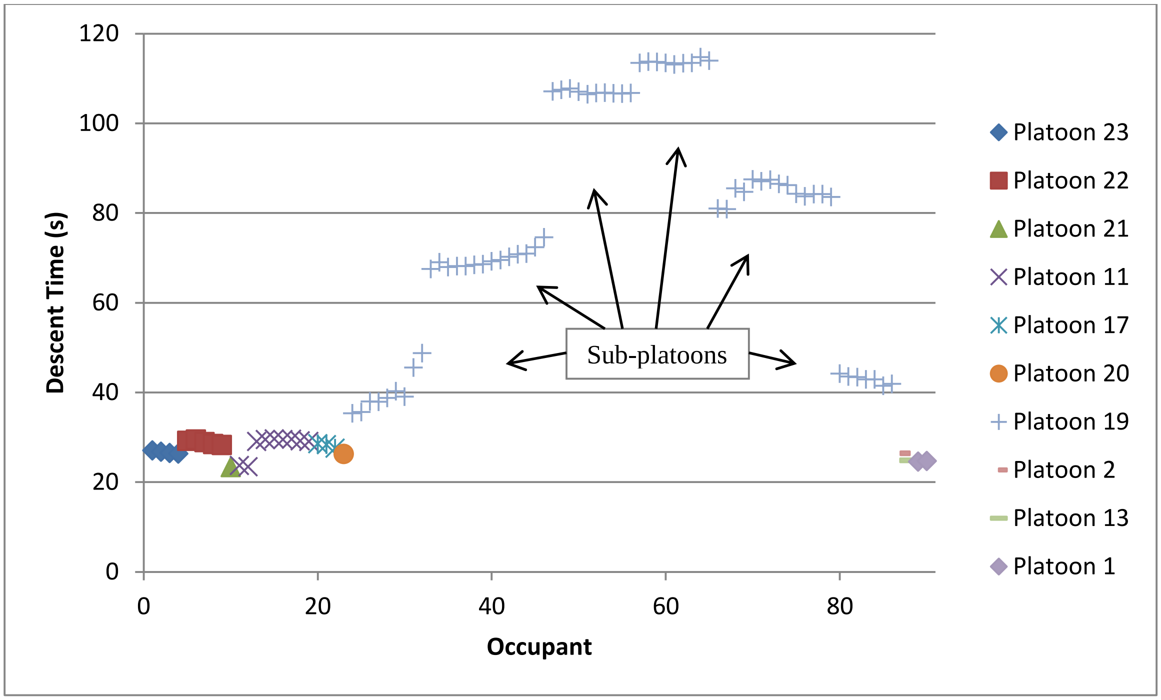


Figure 5-13: Stairwell 4B Platoon Descent Times from Floor 16 to 14

Figure 5-14 illustrates the descent times of the platoons from floor 14 to12. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 14:

- Platoons 1, 2, and 13 remain unchanged.
- Platoon 11 fragments creating platoons 26 and 27.
- Platoons 17 and 20 merge with platoon 26 and add new occupants.
- Platoons 21 and 22 merge and add new occupants creating platoon 28.
- Platoons 19 and 23 add new occupants.
- Two new platoons emerge, platoons 24 and 25.

During this descent, a queue is again present indicated by the increase in the descent times beginning in platoon 28. Also, sub-platoons are present in platoons 19, 26, and 38. Each of the sub-platoons travel in equilibrium with the exception of the first two sub-platoons in platoon 19, which travel in compression.

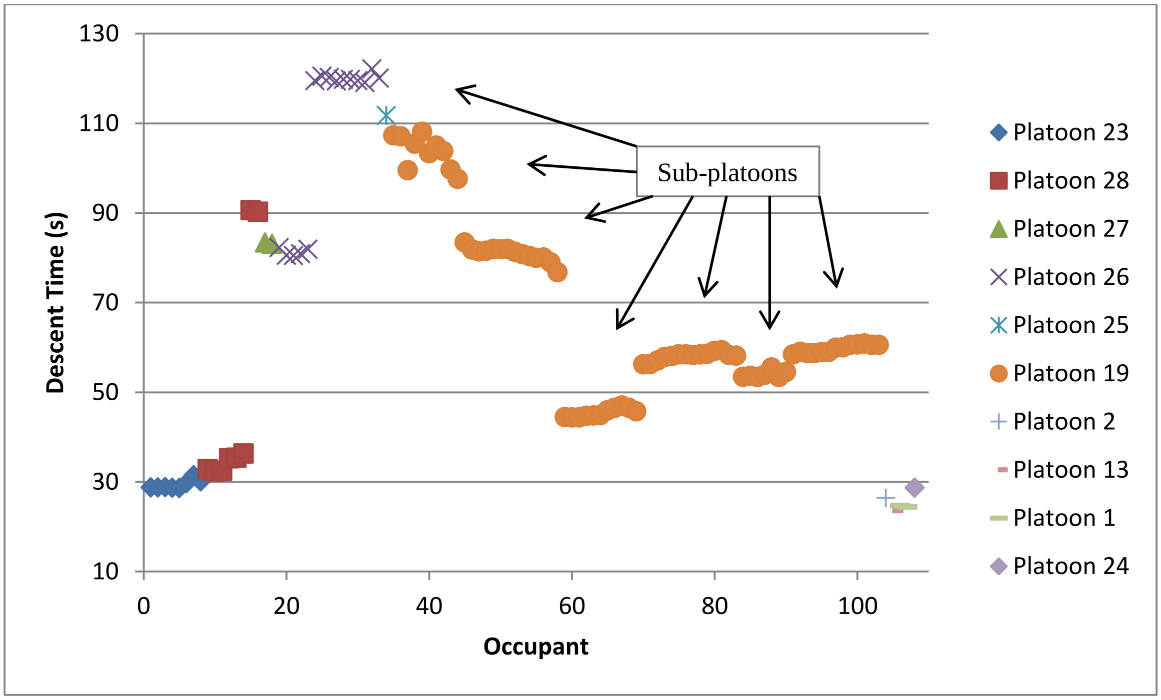


Figure 5-14: Stairwell 4B Platoon Descent Times from Floor 14 to 12

Figure 5-15 illustrates the descent times of the platoons from floor 12 to 10. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 12:

- Platoons 1, 2, 13, and 24 remain unchanged.
- Platoons 19, 23, 25, 26, 27, and 28 merge together and add new occupants creating platoon 29.
- Five new platoons emerge, platoons 30, 31, 32, 33, and 34.

Again during this descent a queue is present indicated by the increase in the descent times peaking at 135.5 seconds in platoon 29. Again, sub-platoons are recognizable in platoons 29 and 31. During this descent, platoons 31, 32, and 33 elongate and platoon 29 travels in compression.

However, all of the sub-platoons present travel in equilibrium. At this point, the upper half of the camera views in stairwell 4B have been analyzed; therefore, no new platoons will be analyzed for the lower half.

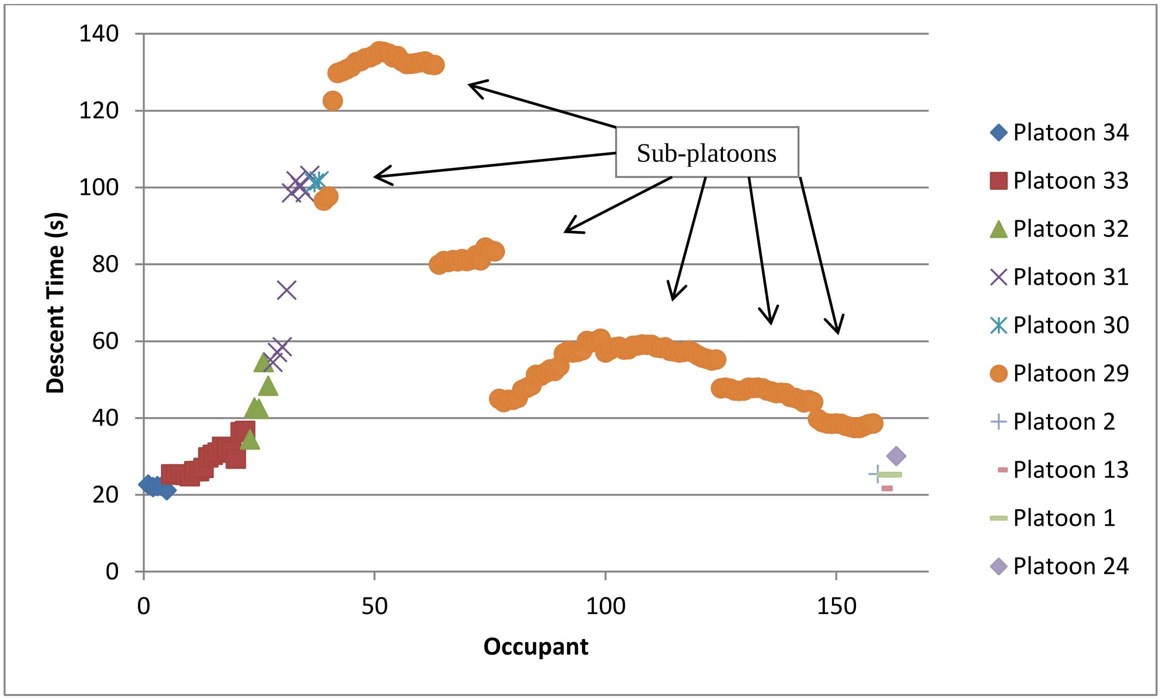


Figure 5-15: Stairwell 4B Platoon Descent Times from Floor 12 to 10

The descent times of the platoons from floor 10 to 8 is shown in Figure 5-16. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 10:

- Platoons 1, 2, 13, 24, and 34 remain unchanged.
- Platoons 29, 30, 31, 32, and 33 merge together and add new occupants creating platoon 35.

During this descent, a queue is again present indicated by the spike in the descent times in platoon 35. Also, four sub-platoons exist in platoon 35. The first and third sub-platoons travel in elongation, the second and fourth sub-platoons travel in compression.

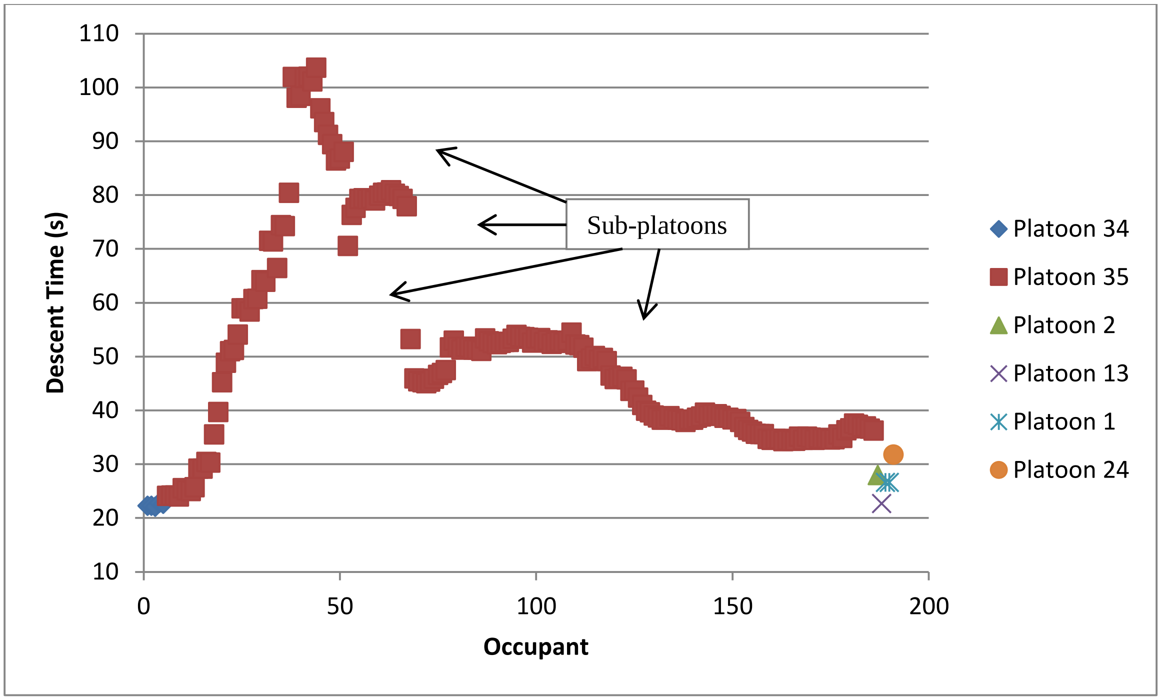


Figure 5-16: Stairwell 4B Platoon Descent Times from Floor 10 to 8

Figure 5-17 illustrates the descent times of the platoons from floor 8 to 6. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 8:

- Platoons 1, 13, and 24 remain unchanged.
- Platoon 35 fragments creating platoons 36 and 37.
- Platoon 2 merges with platoon 36.
- Platoons 34 and 37 add new occupants.

During this descent, a queue is present in platoon 37 indicated by the descent times peaking at 60.5 seconds. Also, four sub-platoons are present in platoon 37. The first three sub-platoons travel in elongation while the fourth travels in equilibrium.

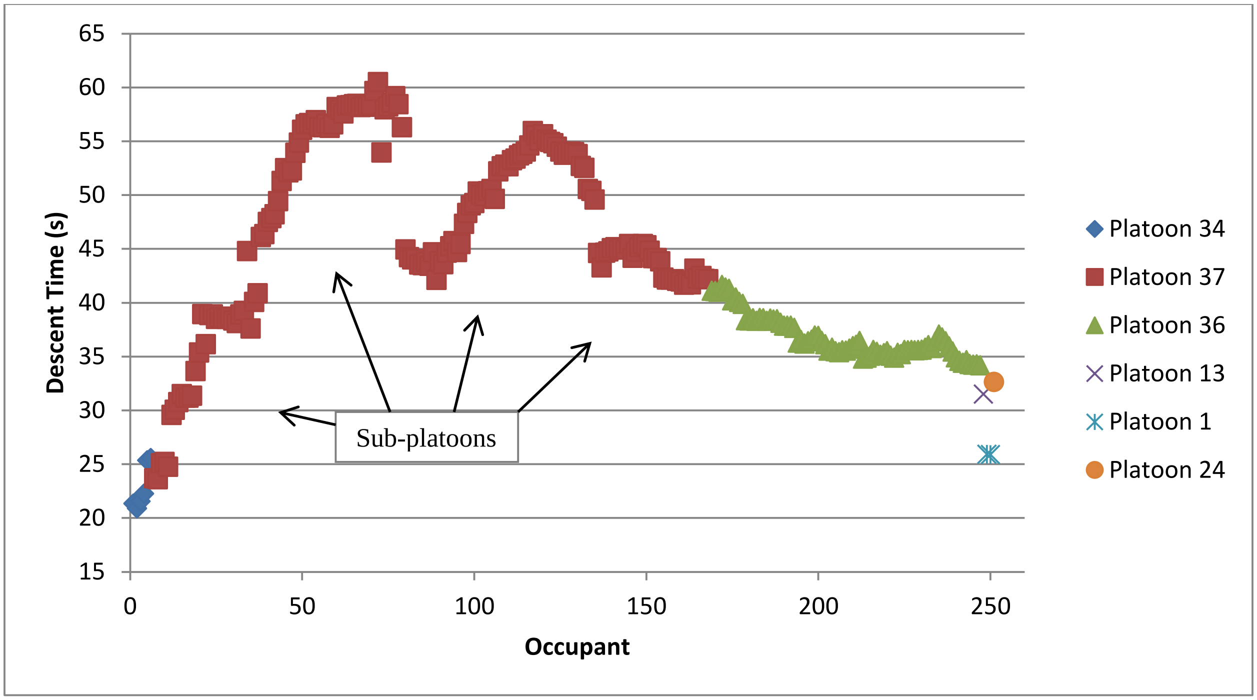


Figure 5-17: Stairwell 4B Platoon Descent Times from Floor 8 to 6

Figure 5-18 illustrates the descent times of the platoons from floor 6 to 4. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 6:

- Platoons 1, 13, and 24 again remain unchanged.
- Platoons 34, 36, and 37 merge together and add new occupants creating platoon 38.

During the descent from floor 6 to 4, the queue from the floors above has dissipated since the descent times in platoon 38 remain close to 40 seconds. Also, two sub-platoons are present in platoon 38. The first sub-platoon travels in elongation while the second travels in compression.

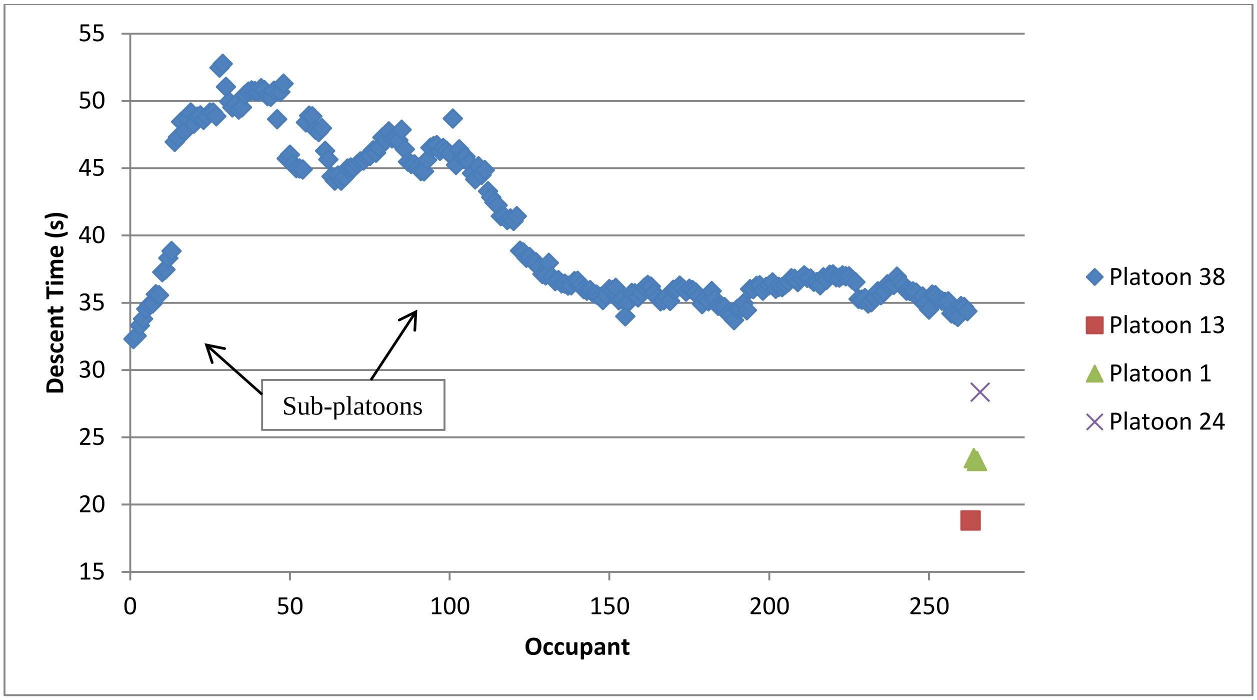


Figure 5-18: Stairwell 4B Platoon Descent Times from Floor 6 to 4

Figure 5-19 illustrates the final descent times of the platoons from floor 4 to 1. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 4:

- Platoons 1, 13, and 24 have remained unchanged.
- Platoon 38 adds new occupants.

During this descent all of the platoons travel in equilibrium as they reach the exit floor. The largest platoon appears to travel in equilibrium as all of the occupants reach the exit. Also, queues are not present because all of the descent times remain near the range of 60 to 65 seconds.

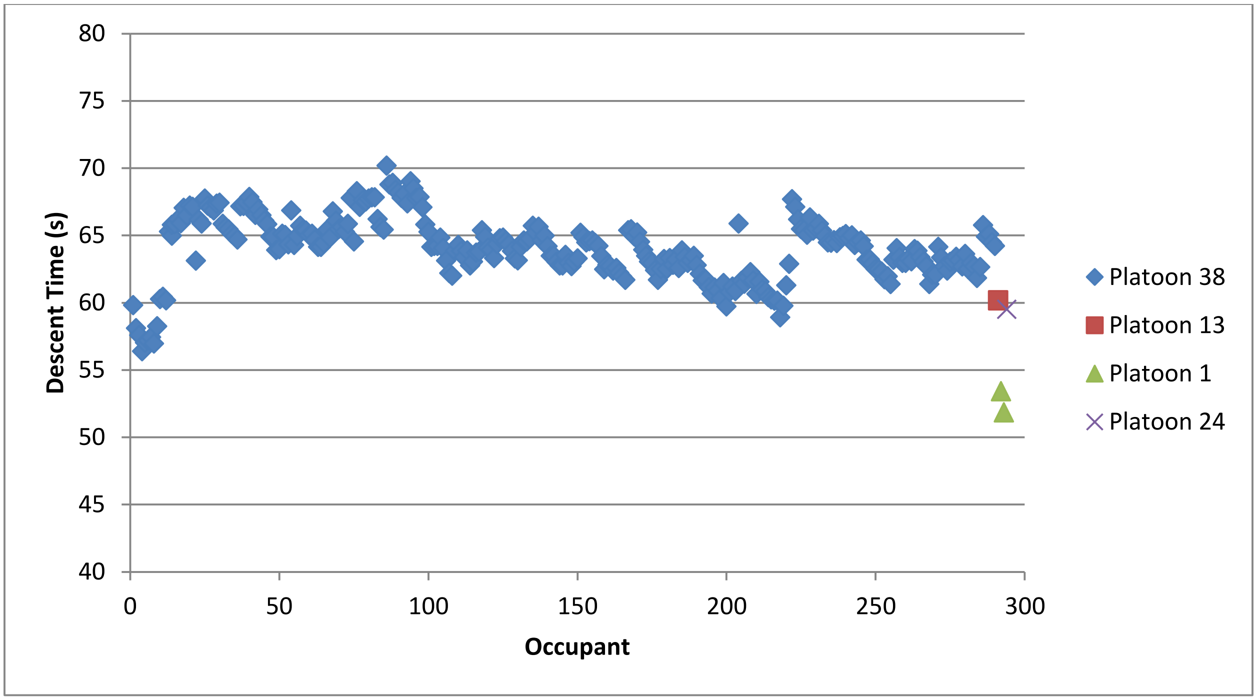


Figure 5-19: Stairwell 4B Platoon Descent Times from Floor 4 to 1

5.1.3 Discussion

The results of the platoon analysis for the two stairwells of Building 4 indicate that a trend exists to describe how platoons travel and whether they change or remain cohesive. In multiple circumstances, platoons that elongated during a descent of two floors fragmented. For example, in stairwell 4A platoons 4, 7, 9, and 42 all travel in elongation and later fragmented. Furthermore, platoons 30, 35, 38, and 41 all have an increasing and decreasing trend in their descent times. The initial occupants of these platoons who have an increasing trend in descent times travel in elongation and later fragment during their descent. These patterns also exist in stairwell 4B. The first sub-platoon of platoon 35, which travels in elongation, fragments during its descent.

Conversely, another pattern exists between platoons which travel in compression and merge together between camera views. In stairwell 4A from floor 18 to 16, platoons 10, 19, and 20 have a trend of compression as each platoon has a higher descent time then the following platoon. Each of these platoons merges together during their descent. Also from floor 16 to 14, platoons 13, 22, 23, 24, and 25 have a compressing trend and later merge together. This pattern also exists in stairwell 4B from floor 18 to 16 as platoons 3, 4, 5, 14, and 15 have a compressing trend and later merge together. Furthermore, from floor 14 to 12, platoons 19, 25, and 26 together travels in compression and merge together during their descent.

A final pattern exists where the last platoons to exit the stairwell remain unchanged during their entire descent. For example, in stairwell 4A platoons 1, 2, and 29 are the last three platoons to exit and remain cohesive during their descent. However, these platoons do not begin their evacuation until more than 4 minutes after the alarm sounded, which allowed for a less crowded stairwell as queues had time to dissipate. A similar pattern exists in stairwell 4B as platoons 1, 13, and 24 were the last three to exit the stairwell and remain unchanged during their descent. Again, these platoons did not begin their evacuation until at least 7 minutes after the alarm sounded, which allowed for any queues to dissipate.

In analyzing how the platoons of Building 4 changed as they exited each camera view, the total number of platoons identified and the number of those platoons that remain unchanged, add new occupants, merged, and/or fragmented is recorded. Table 5-1 illustrates the changes occurring to the platoons in stairwell 4A as they descend from one camera view to the next. For this table, the number of platoons which remain unchanged, add new occupants, merge, and/or fragment is associated to the total identified for each row. For example, if two platoons are listed as merged, this signifies that two of the total platoons for the row resulted in a merge of some platoons from the previous floor. Also, if two platoons are listed as fragmented, then two platoons resulted in fragmentation from one platoon from above. This table also includes the number of new platoons identified as well as the number of one-person platoons.

	Number of Platoons						
Floor	Total	Unchanged	Added New Occupants	Merged	Fragmented	One-person	New
22 to 20	6					3	6
20 to 18	11	3	2	0	2	4	4
18 to 16	14	3	2	2	6	5	1
16 to 14	11	3	3	3	0	5	4
14 to 12	8	2	2	2	0	3	3
12 to 10	6	3	1	1	2	3	1
10 to 8	6	3	3	1	2	2	0
8 to 6	7	3	2	2	4	2	0
6 to 4	6	3	2	1	0	2	0
4 to 2	9	4	2	0	5	3	0

Table 5-1: Platoon Variations for Stairwell 4A

A total of 84 platoons were identified in stairwell 4A. Neglecting the first descent from floor 22 to 20 because no changes could take place during this descent, 27 (34.6%) platoons remained unchanged, 19 (24.4%) added new occupants, 12 (15.4%) resulted in a merge, and 21 (26.9%) resulted in fragmentation out of 78 platoons. Therefore, platoons most frequently remained unchanged and the least amount resulted in a merge. Pie charts illustrating the platoon variations for all stairwells are included in Appendix C.

Table 5-2 illustrates the associated sizes of the platoons for stairwell 4A. Of the 84 platoons identified, platoons most frequently are one-person platoons and the least amount of platoons contains 3-5 occupants. Pie charts illustrating the platoon sizes for all stairwells are included in Appendix D.

Number of Occupants	Number of Platoons
1 Person	32 (38.1%)
2 Persons	16 (19%)
3-5 Persons	9 (10.7%)
6-10 Persons	10 (11.9%)
11+ Persons	17 (20.2%)
Total	84

Table 5-2: Platoon Sizes for Stairwell 4A

A total of 75 platoons were identified in stairwell 4B. Neglecting the first descent from floor 22 to 18 because no changes could take place during this descent, 31 (49.2%) platoons remained unchanged, 15 (23.8%) added new occupants, 9 (14.3%) resulted in a merge, and 4 (6.3%) resulted in fragmentation out of 63 platoons. Therefore, platoons most frequently remained unchanged and the least amount resulted in fragmentation. Table 5-3 illustrates the changes occurring to the platoons in stairwell 4B as they descend from one camera view to the next.

	Number of Platoons						
Floor	Total	Unchanged	Added New Occupants	Merged	Fragmented	One-person	New
22 to 18	12					4	12
18 to 16	13	6	2	1	0	5	5
16 to 14	10	4	3	2	0	4	3
14 to 12	10	3	4	2	2	4	2
12 to 10	10	4	1	1	0	3	5
10 to 8	6	5	1	1	0	3	0
8 to 6	6	3	2	1	2	2	0
6 to 4	4	3	1	1	0	2	0
4 to 1	4	3	1	0	0	2	0

Table 5-3: Platoon Variations for Stairwell 4B

Table 5-4 illustrates the associated sizes of the platoons for stairwell 4B. Of the 75 platoons identified, the greatest number of platoons are one-person platoons and the least amount of platoons contains 6-10 occupants.

Number of Occupants	**Number of Platoons**
1 Person	29 (38.7%)
2 Persons	17 (22.7%)
3-5 Persons	11 (14.7%)
6-10 Persons	7 (9.3%)
11+ Persons	11 (14.7%)
Total	75

Table 5-2: Platoon Sizes for Stairwell 4B

Overall both stairwells 4A and 4B have common trends in the platoon variations and sizes. Platoons for both stairwells most frequently are one-person platoons. Also, platoons most frequently remain unchanged during the descent between camera views.

5.2 Platoon Analysis of Building 5

The following section contains an analysis of the platoons identified in Building 5 using the methodology described in Section 4.3 and 4.4. All of the changes in the descent of the platoons for Building 5 are described in Section 5.2.3. As was the case in Building 4, each of the two stairwells in Building 5 is identical with the exception that firefighter counterflow is present in stairwell 5B.

5.2.1 Stairwell 5A

A total of 6 platoons are identified exiting the camera view at floor 9. Figure 5-20 illustrates the descent times of the platoons from floor 9 to 7. Platoon 2 is a one-person platoon, which continuously passes others indicated by the lower descent time than the nearby occupants of platoons 1 and 3. Four sub-platoons are present in platoon 1 and two sub-platoons are present in platoon 3. All of the sub-platoons travel in equilibrium with the exception of the second sub-platoon in platoon 3 which travels in elongation. Platoon 1 travels in compression while platoon 3 travels in elongation. Also, a queue is present during this descent as the descent times greatly increase in platoons 1 and 3.

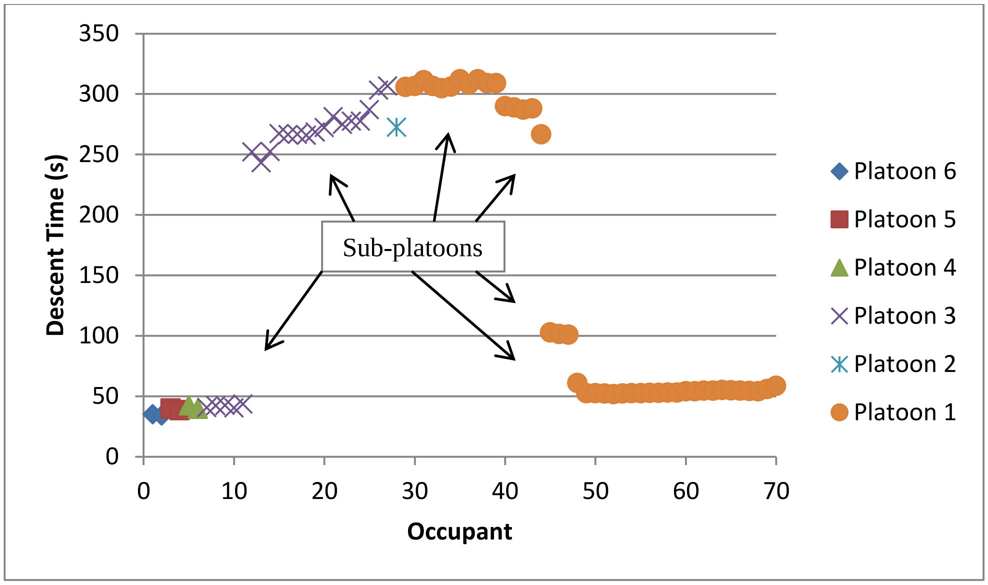


Figure 5-20: Stairwell 5A Platoon Descent Times from Floor 9 to 7

Figure 5-21 illustrates the descent times of the platoons from floor 7 to 5. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 7:

- Platoon 5 remains unchanged.
- Platoon 3 fragments creating platoons 8 and 9.
- Platoon 1 merges with platoon 8.
- Platoons 2 and 4 merge with platoon 9.
- Platoons 6, 8, and 9 add new occupants.
- Ten new platoons emerge, platoons 7, 10, 11, 12, 13, 14, 15, 16, 17, and 18.

During this descent, platoons 13, 14, and 15 are passing platoons indicated by the lower descent times than the platoons nearby. Also, platoon 10 is continuously passed by multiple occupants indicated by the higher descent time than the occupants nearby in platoon 9.

Similar to the descent times from floor 9 to 7, a queue is present indicated by the increasing descent times starting in platoon 6. Two sub-platoons are present in platoon 9. All of the platoons and sub-platoons travel in equilibrium with the exception of platoon 6, which travels in elongation.

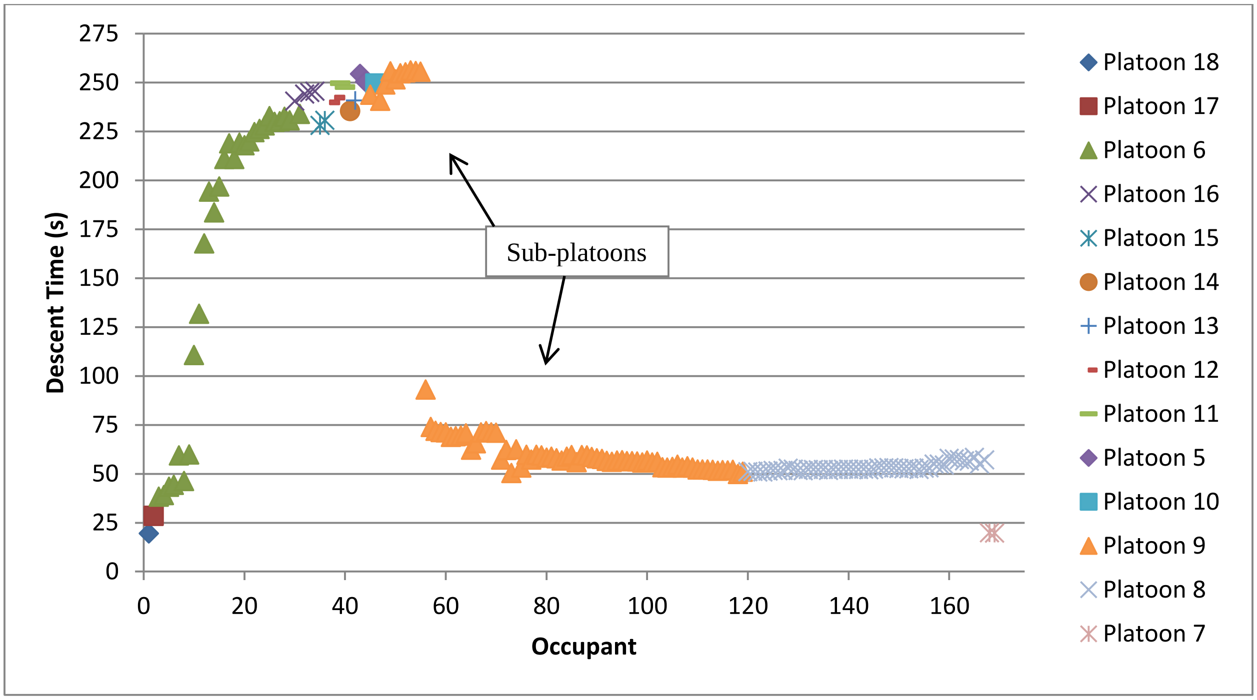


Figure 5-21: Stairwell 5A Platoon Descent Times from Floor 7 to 5

Figure 5-22 illustrates the descent times of the platoons from floor 5 to 3. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 5:

- Platoons 7, 13, and 18 remain unchanged.
- Platoon 9 fragments into platoons 19 and 21.
- Platoon 6 fragments into platoons 21, 23, and 27.
- Platoons 5, 10, 11, 12, 14, 15, and 16 merge with platoon 21.
- Platoon 17 merges with platoon 27.
- Platoons 8, 21, and 27 add new occupants.
- Five new platoons emerge, platoons 20, 22, 24, 25, and 26.

During this descent, platoons 13 and 22 are passing platoons indicated by the lower descent times compared to the other occupants nearby. Also, platoons 19, 20, 23, 24, 25, and 26 are platoons which are continuously passed by other occupants. A queue again is present indicated by the increasing descent times in platoon 27. During this descent, platoons 24, 25, and 27 travel in elongation and platoon 21 travels in elongation. All other platoons travel in equilibrium. At this point, the upper half of the camera views in stairwell 5A have been analyzed; therefore, no new platoons will be analyzed for the lower half.

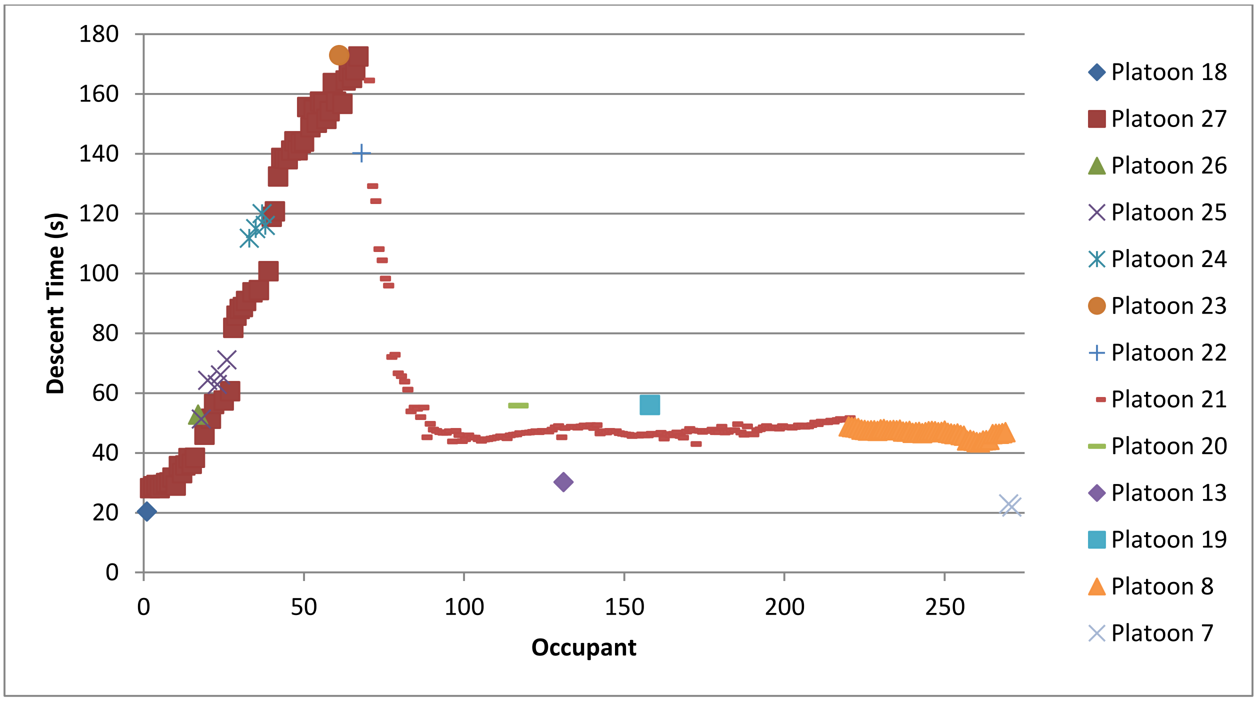


Figure 5-22: Stairwell 5A Platoon Descent Times from Floor 5 to 3

Figure 5-23 illustrates the final descent times of the platoons from floor 3 to 1. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 3:

- Platoons 7, 13, and 26 remain unchanged.
- Platoon 21 fragments into platoons 28 and 29.

- Platoon 25 fragments into platoons 29, 30, 31, and 32.
- Platoon 27 fragments into platoons 29, 30, 32, 33, and 34.
- Platoons 8, 19, 20, 22, 23, and 24 merge with platoon 29.
- Platoons 29, 30, and 32 have merged occupants from the fragmented platoons.
- Platoons 18, 29, 31, 32, 33, and 34 add new occupants.

During this descent, platoons 13, 30, and 32 are passing platoons indicated by the lower descent times with respect to the occupants in the nearby platoons. Conversely, platoons 26, 28, 33 are platoons which are continuously passed by multiple occupants in the nearby platoons. A queue is again present in this descent indicated by the increasing descent times in platoon 34. Platoons 31, 32, 33, and 34 travel in elongation while platoon 29 travels in compression.

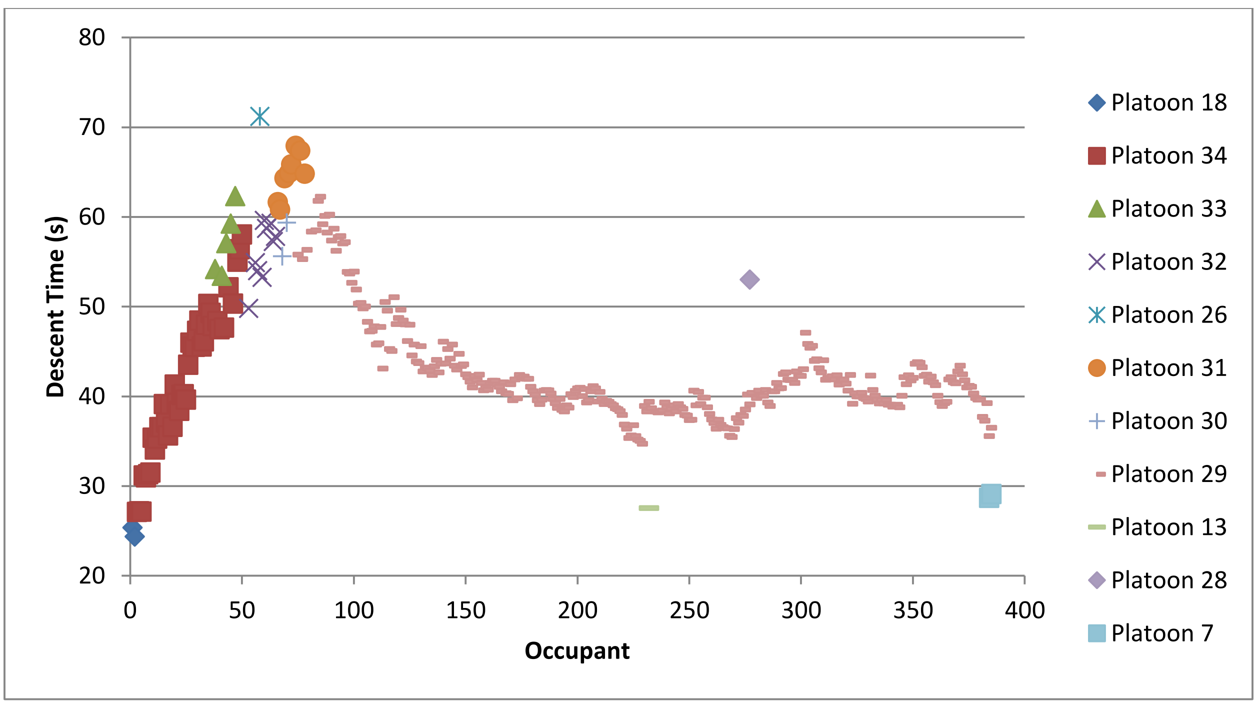


Figure 5-23: Stairwell 5A Platoon Descent Times from Floor 3 to 1

5.2.2 Stairwell 5B

During the descent from floor 9 to 7, a total of 9 platoons are identified exiting the camera view at floor 9. Figure 5-24 illustrates the descent times of the platoons from floor 9 to 7. Platoons 1, 2, 5, 7, and 9 are one-person platoons. Platoon 5 is continuously passed platoon indicated by the higher descent time higher than the occupants of platoon 6.

Similar to stairwell 5A, a queue is present during this descent beginning in platoon 6. Also, each of the 9 platoons travel in equilibrium with the exception of platoons 6 and 8 which travel in elongation.

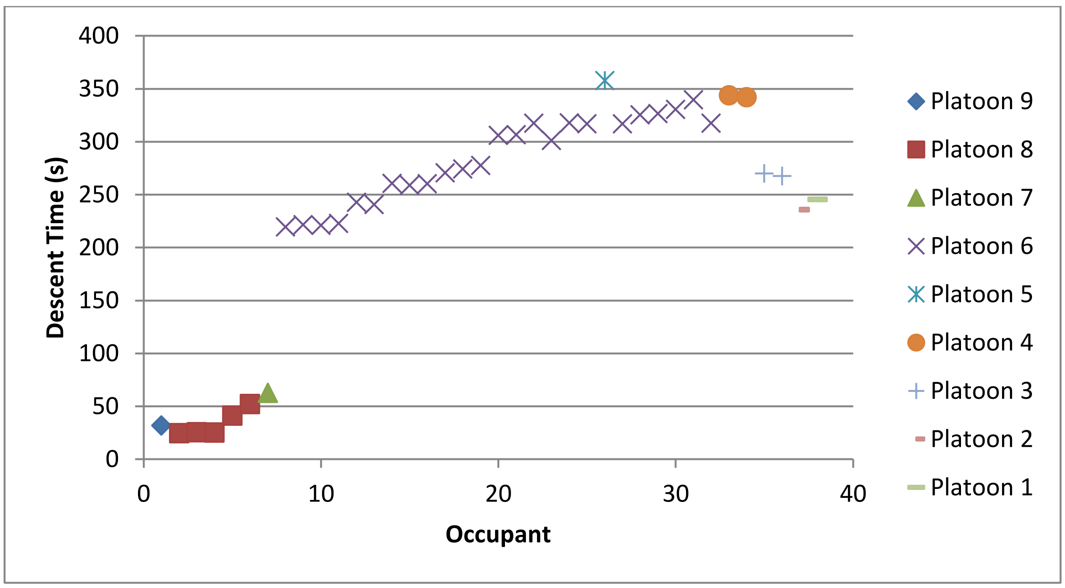


Figure 5-24: Stairwell 5B Platoon Descent Times from Floor 9 to 7

Figure 5-25 illustrates the descent times of the platoons from floor 7 to 5. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 7:

- Platoons 1-7 and 9 merge and add new occupants creating platoon 18.
- Platoon 8 fragments creating platoons 11, 12, 14, and 18.
- Six new platoons emerge, platoons 10, 13, 15, 16, 17, and 19.

During this descent, platoons 10, 11, 12, 14, and 16 are passing platoons indicated by the lower descent times with respect to the occupants nearby in platoon 18. Also, platoons 13, 15, 17 are platoons which are continuously passed by other occupants in platoon 18 indicated by their higher descent times.

A queue is again present during this descent indicated by the increasing descent times in platoon 18. Also, sub-platoons exist in platoon 18. The first sub-platoon travels in elongation and the latter three travel in equilibrium.

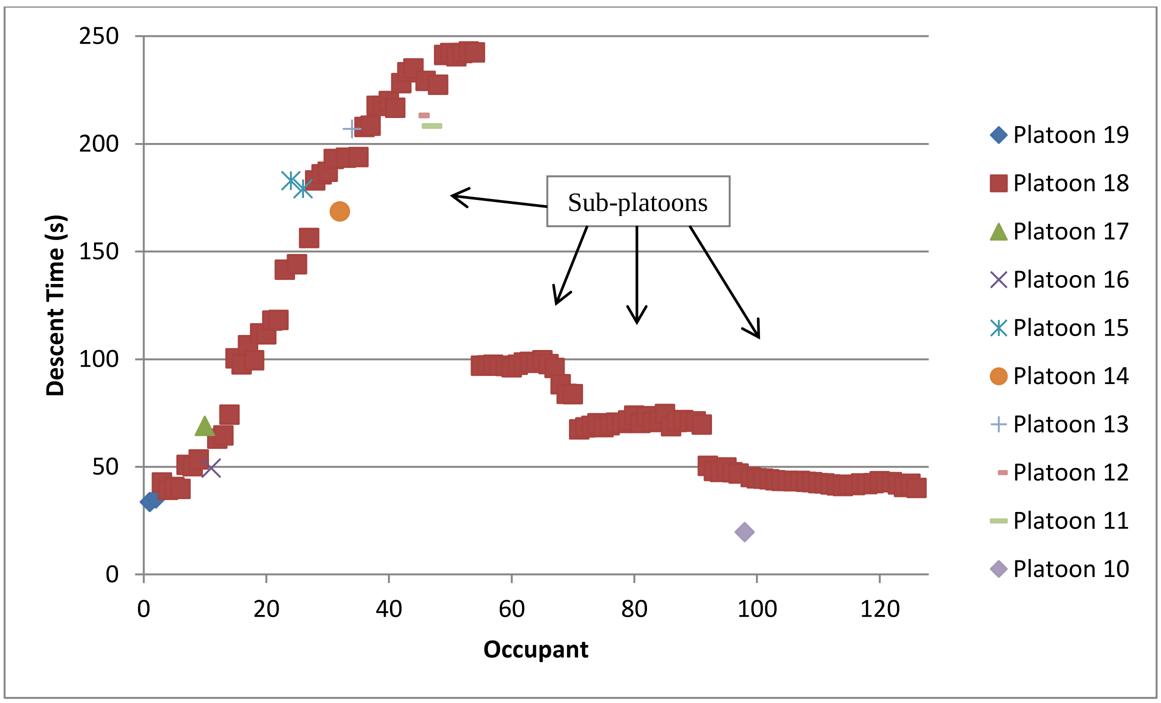


Figure 5-25: Stairwell 5B Platoon Descent Times from Floor 7 to 5

Figure 5-26 illustrates the descent times for the platoons from floor 5 to 3. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 5:

- Platoon 10 remains unchanged.
- Platoons 11-17 merge together and add new occupants creating platoon 27.
- Platoon 18 fragments creating platoons 21 and 27.

- Platoon 19 fragments creating platoons 25 and 27.
- Six new platoons emerge, platoons 20, 22, 23, 24, 26, and 28.

During this descent, platoons 10, 20, 21, 24, and 25 are passing platoons indicated by the lower descent times with respect to the occupants nearby in platoon 27. Also, platoons 22, 23, and 26 are continuously passed by occupants in platoon 27 indicated by the higher descent times.

Again during this descent a queue is present indicated by the increasing descent times in platoon 27. Counterflow is again present in this stairwell as in stairwell 4A. Three firefighters pass by occupants 235 and 236 at floor 3 causing these occupants to stop and allow the firefighters to continue upward. The effect of counterflow creates a sub-platoon in platoon 27 consisting of the last 11 occupants. At this point, the upper half of the camera views in stairwell 5B have been analyzed; therefore, no new platoons will be analyzed for the lower half.

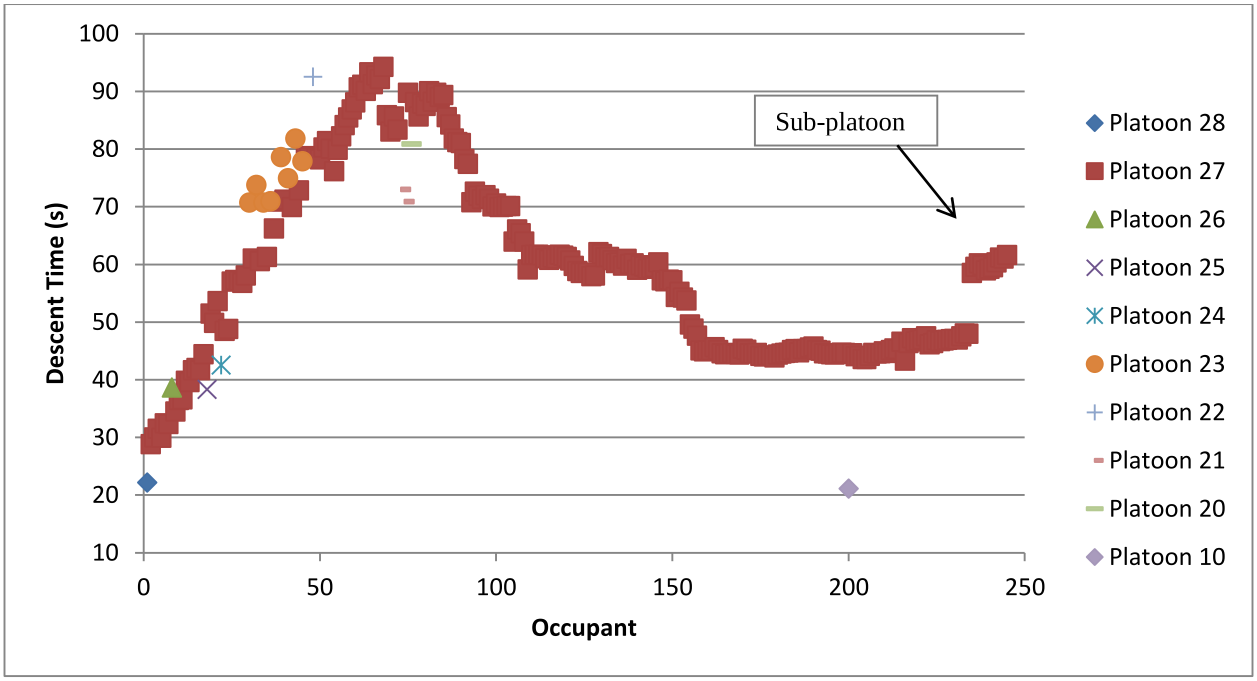


Figure 5-26: Stairwell 5B Platoon Descent Times from Floor 5 to 3

Figure 5-27 illustrates the descent times of the platoons from floor 3 to 1. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 3:

- Platoon 10 remains unchanged again.
- Platoon 27 fragments creating platoons 29 and 30.
- Platoons 20-25 merge and add new occupants creating platoon 30.
- Platoons 26 and 28 add new occupants

During this descent, platoon 10 is a passing platoon and platoon 26 is passed platoon.

During this descent, sub-platoons are present in platoons 29 and 35. Platoon 35 has four sub-platoons, the first three sub-platoons elongate and the last travels in compression. Platoon 29 has 3 sub-platoons, the first and third travel in equilibrium and the second travels in elongation. Counterflow is again present during this descent in platoon 29 as three firefighters pass by occupants 273 and 274 in the camera view at floor 1. The effect of counterflow halts the descent of these occupants which creates the second sub-platoon of platoon 29.

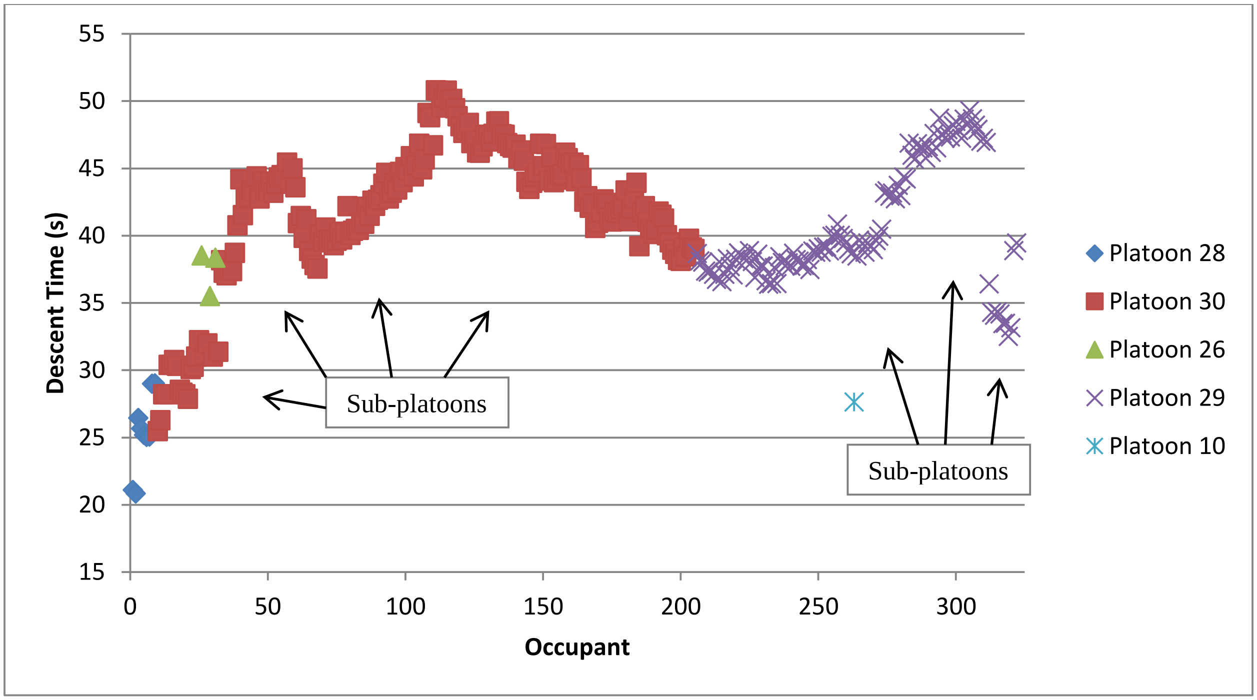


Figure 5-27: Stairwell 5B Platoon Descent Times from Floor 3 to 1

5.2.3 Discussion

The results of the platoon analysis for the two stairwells of Building 5 indicate similar trends as in Building 4. In multiple circumstances, platoons that elongated between two camera views have fragmented during their descent. For example, in stairwell 5A platoons 3, 6, 27, and 35 all travel in elongation and later fragment. Also, in stairwell 5B platoon 8 and the first sub-platoon of platoon 27 travels in elongation and have fragmented during their descent.

Conversely, the pattern of a platoon traveling in compression in some cases leads to a merge. For example, in stairwell 5A platoons 1 and 9 travel in compression and merge with other platoons during their descent. Also, in stairwell 5B from floor 9 to 7, platoons 1-4 have a trend of compression as each platoon has a higher descent time than the following platoon. Each of these platoons merges with other platoons. Furthermore, the middle set of occupants descending in platoons 18 and 27 travels in compression and later merges with other platoons.

Finally, in stairwell 5A, the last platoon to exit the stairwell remained unchanged, similar to the final platoons in Building 4. Platoon 7 remained unchanged during its entire descent; however, this platoon did not begin to evacuate until 12 minutes after the alarm sounded, which allowed for a less crowded stairwell as queues had time to dissipate. Conversely, platoon 13 in stairwell 5A and platoon 10 in stairwell 5B remained unchanged but did not exit with the last platoons. These platoons were one-person passing platoons which continuously passed occupants before exiting.

A total of 44 platoons were identified in stairwell 5A. Neglecting the first descent from floor 9 to 7 because no changes could take place during this descent, 7 (18.4%) platoons remained unchanged, 10 (26.3%) added new occupants, 7 (18.4%) resulted in a merge, and 13 (34.2%) resulted in fragmentation out of 38 platoons. Therefore, the most frequent variation of the platoons resulted in fragmentation and the least amount resulted in a combination of remaining unchanged or merging. Table 5-5 illustrates the changes occurring to the platoons in stairwell 5A as they descend from one camera view to the next.

	Number of Platoons						
Floor	Total	Unchanged	Added New Occupants	Merged	Fragmented	One-person	New
9 to 7	6					1	6
7 to 5	14	1	3	2	2	5	10
5 to 3	13	3	1	2	4	7	5
3 to 1	11	3	6	3	7	2	0

Table 5-5: Platoon Variations for Stairwell 5A

Table 5-6 illustrates the associated sizes of the platoons for stairwell 5A. Of the 44 platoons identified, the greatest number of platoons are one-person platoons and the least amount of platoons contains 6-10 occupants.

Number of Occupants	Number of Platoons
1 Person	16 (36.4%)
2 Persons	11 (25%)
3-5 Persons	5 (11.4%)
6-10 Persons	2 (4.5%)
11+ Persons	10 (22.7%)
Total	44

Table 5-6: Platoon Sizes for Stairwell 5A

A total of 34 platoons were identified in stairwell 5B. Neglecting the first descent from floor 9 to 7 because no changes could take place during this descent, 2 (8%) platoons remained unchanged, 6 (24%) added new occupants, 3 (12%) resulted in a merge, and 9 (36%) resulted in fragmentation out of 38 platoons. Therefore, the most frequent variation of the platoons resulted in fragmentation and the least amount remained unchanged. Table 5-7 illustrates the changes occurring to the platoons in stairwell 5B as they descend from one camera view to the next.

	Number of Platoons						
Floor	Total	Unchanged	Added New Occupants	Merged	Fragmented	One-person	New
9 to 7	9					5	9
7 to 5	10	0	1	1	4	7	6
5 to 3	10	1	2	1	3	7	6
3 to 1	5	1	3	1	2	1	0

Table 5-7: Platoon Variations for Stairwell 5B

Table 5-8 illustrates the associated sizes of the platoons for stairwell 5B. Of the 34 platoons identified, the greatest number of platoons are one-person platoons and the least amount of platoons contains 3-5 and 6-10 occupants.

Number of Occupants	Number of Platoons
1 Person	20 (58.8%)
2 Persons	5 (14.7%)
3-5 Persons	2 (5.9%)
6-10 Persons	2 (5.9%)
11+ Persons	5 (14.7%)
Total	34

Table 5-8: Platoon Sizes for Stairwell 5B

Overall both stairwells 5A and 5B have common trends in the platoon variations and sizes. Platoons for both stairwells are most frequently one-person platoons. Also, platoons most frequently resulted in fragmentation during the descent between camera views.

5.3 Platoon Analysis of Building 6

The following section contains an analysis of the platoons identified in Building 6 using the methodology described in Section 4.3 and 4.4. All of the changes in the descent of the platoons for Building 6 are described in Section 5.3.3. As described in Chapter 3, both stairwells 6_5 and 6_5A are identical, with the exception of the locations of the transfer corridors. Also, participation in the evacuation drill of Building 6 was voluntary.

5.3.1 Stairwell 6_5

Two platoons are identified exiting the camera view at floor 44. Figure 5-28 illustrates the descent times of the platoons from floor 44 to 36. Both platoons travel in equilibrium during this descent.

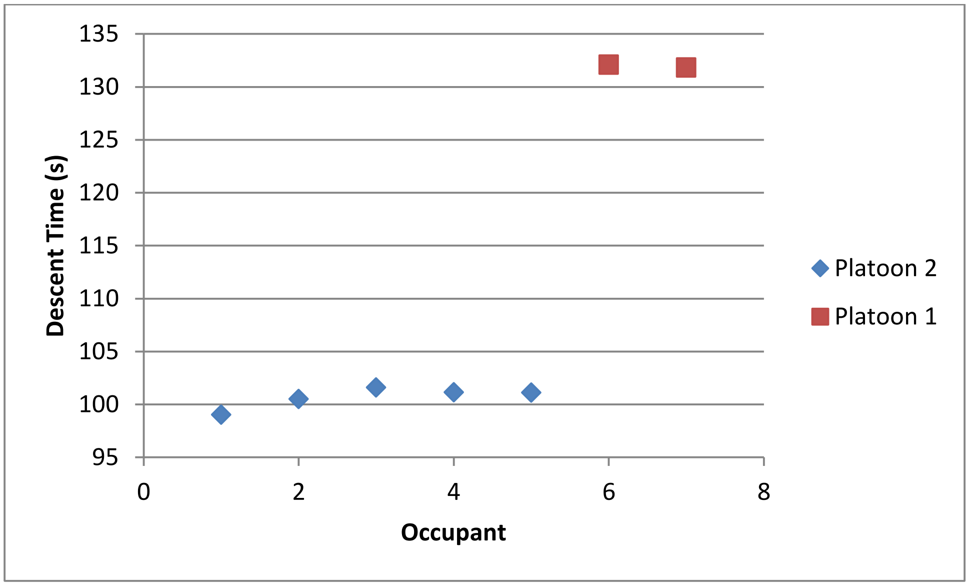


Figure 5-28: Stairwell 6_5 Platoon Descent Times from Floor 44 to 36

Figure 5-29 illustrates the descent times of the platoons from floor 36 to 30. During this descent, two new platoons emerge, platoons 3 and 4. Also, all of the platoons travel in equilibrium. However, one-person sub-platoons are present in platoons 2 and 4. The first occupant of platoon 2 is a sub-platoon which has a lower descent time than the other occupants. Also, the first and sixth occupants of platoon 4 are sub-platoons which have higher descent times than the other occupants.

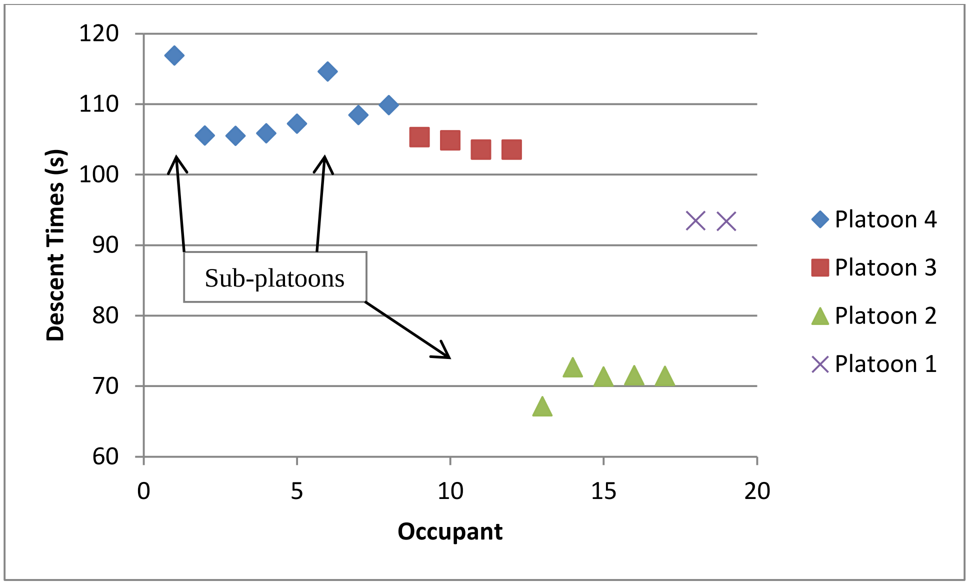


Figure 5-29: Stairwell 6_5 Platoon Descent Times from Floor 36 to 30

Figure 5-30 illustrates the descent times of the platoons from floor 30 to 20. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 30:

- Platoon 1 remains unchanged
- Platoon 2 fragments creating platoons 5 and 6.
- Platoon 4 fragments creating platoons 7 and 8.
- Platoon 3 merges with platoon 7 and adds a new occupant.
- Two new platoons emerge, platoons 9 and 10.

During this descent, all of the platoons travel in equilibrium. In the previous descent, platoon 2 has a lower descent time than platoon 3 and during this descent platoon 2 merged with the last occupants of platoon 3.

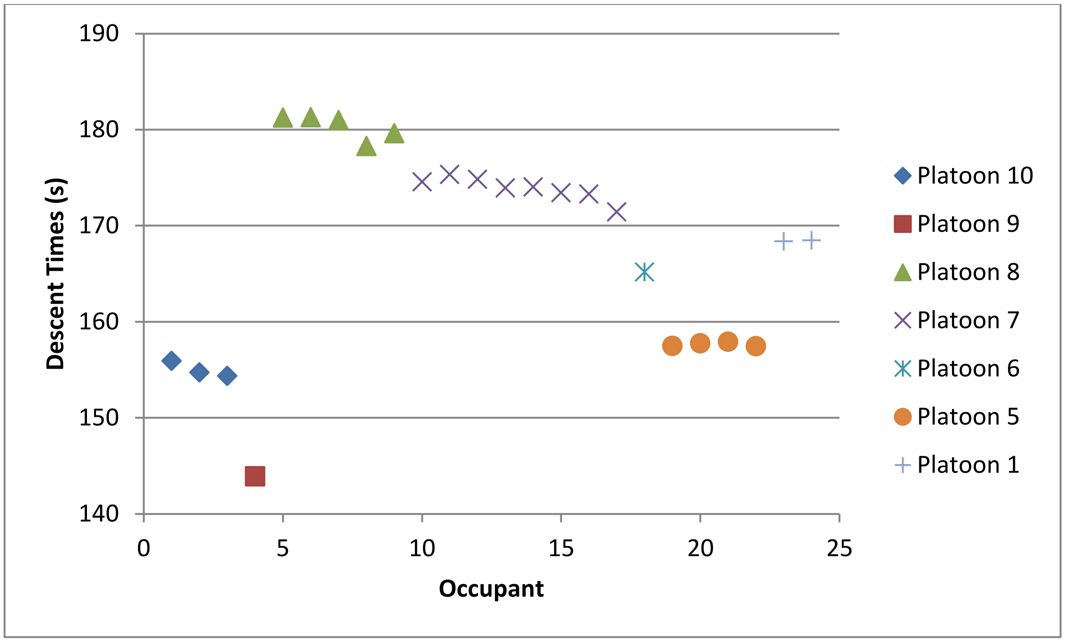


Figure 5-30: Stairwell 6_5 Platoon Descent Times from Floor 30 to 20

Figure 5-31 illustrates the descent times of the platoons from floor 20 to 13. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 20:

- Platoon 1 remains unchanged.
- Platoons 5, 6, 7, and 8 merge together and add a new occupant creating platoon 11.
- Platoons 9 and 10 merge together and add new occupants creating platoon 15.
- Seven new platoons emerge, platoons 12, 13, 14, 16, 17, 18, and 19.

During this descent, two sub-platoons are present in platoons 15, 18 and 19. The first sub-platoon in platoon 18, the second sub-platoon in platoon 19, and platoon 11 all travel in elongation. Conversely, the first sub-platoon in platoon 19 travels in compression. All of the other platoons and sub-platoons travel in equilibrium. During this descent, platoon 17 is continuously passed by the occupants in platoon 18. At this point, the upper half of the camera views in stairwell 6_5 have been analyzed; therefore, no new platoons will be analyzed for the lower half.

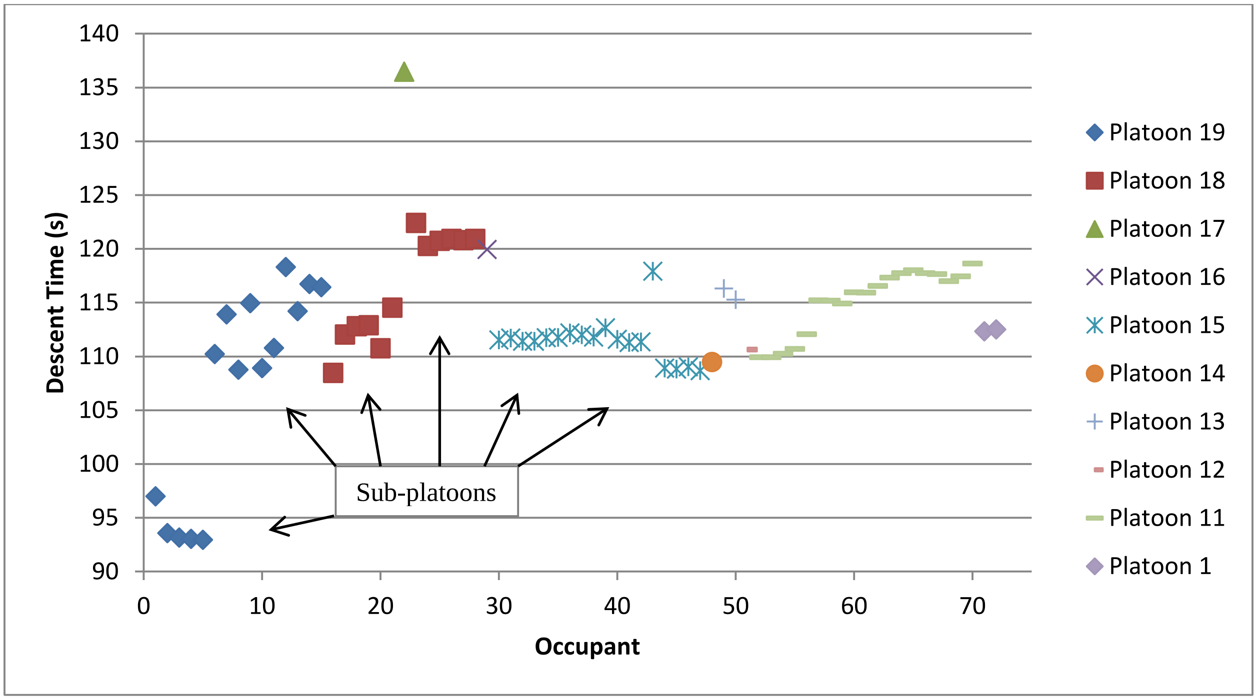


Figure 5-31: Stairwell 6_5 Platoon Descent Times from Floor 20 to 13

Figure 5-32 illustrates the descent times of the platoons from floor 13 to 7. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 13:

- Platoons 1, 14, 15, and 16 remain unchanged.
- Platoon 11 fragments creating platoons 20, 21, and 22.
- Platoon 18 fragments creating platoons 24, 25, 26, and 27.
- Platoon 19 fragments creating platoons 28, 29, and 30.
- Platoons 13 and 14 merge together creating platoon 23.
- Platoon 17 merges with platoon 24.
- Platoon 28 adds new occupants.

During this descent, platoons 15, 23, and 24 travel in elongation. All of the other platoons travel in equilibrium. Sub-platoons are present during this descent in platoons 15 and 22. All of the sub-platoons travel in equilibrium. Also, platoons 20 and 21 are platoons which are continuously passed by platoon 22 as indicated by the higher descent times. Platoon 20 appears to have stopped at some point during this descent because the descent times of the occupants are nearly double those in platoon 22.

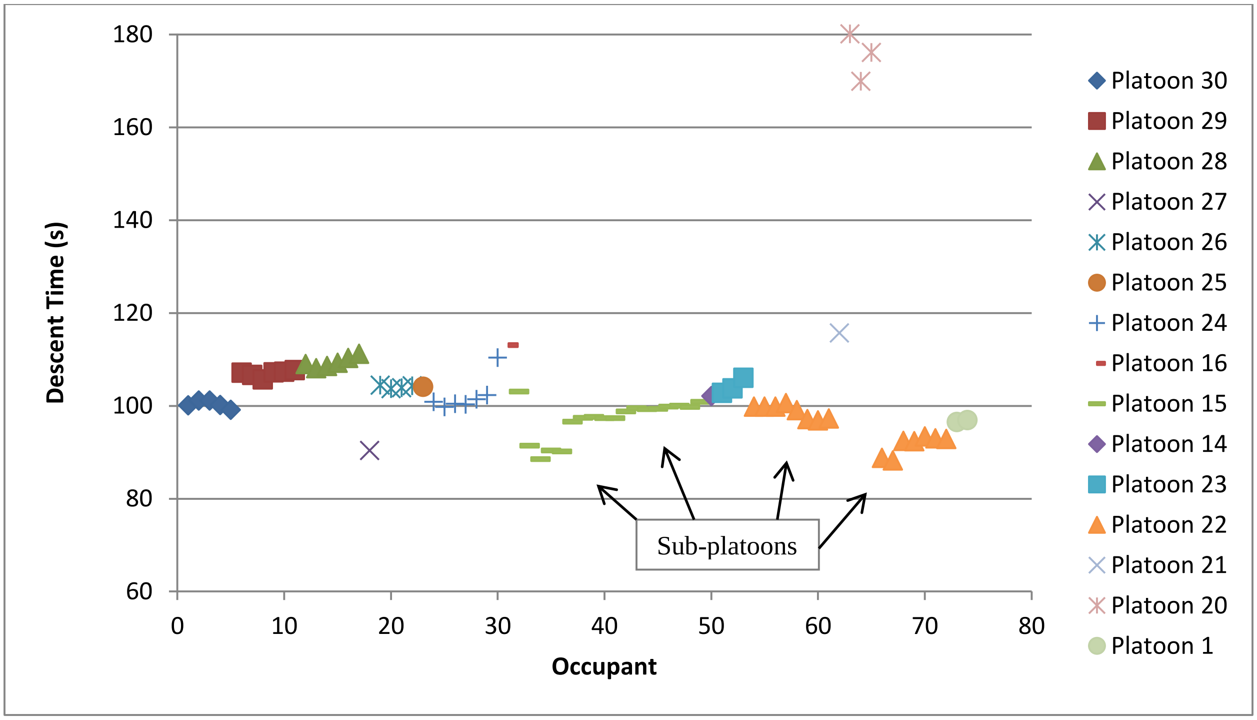


Figure 5-32: Stairwell 6_5 Platoon Descent Times from Floor 13 to 7

Figure 5-33 illustrates the final descent times of the platoons from floor 7 to 1. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 7:

- Platoons 1, 14, 20, 23, 25, 26, 27, and 29 remain unchanged.
- Platoon 24 fragments creating platoons 33 and 34.
- Platoons 21 and 22 merge creating platoon 31.

- Platoons 15 and 16 merge creating platoon 34.
- Platoons 28 and 30 add new occupants.

During this descent, platoons 28 and 31 travel in compression while platoon 32 travels in elongation. All other platoons travel in equilibrium. Two sub-platoons are present in platoon 32 and both travel in equilibrium. Platoon 20 is again a platoon which is passed by platoon 1 before reaching the exit floor. Again this platoon appears to have halted its descent as the descent times are more than double the descent times in the nearby platoons.

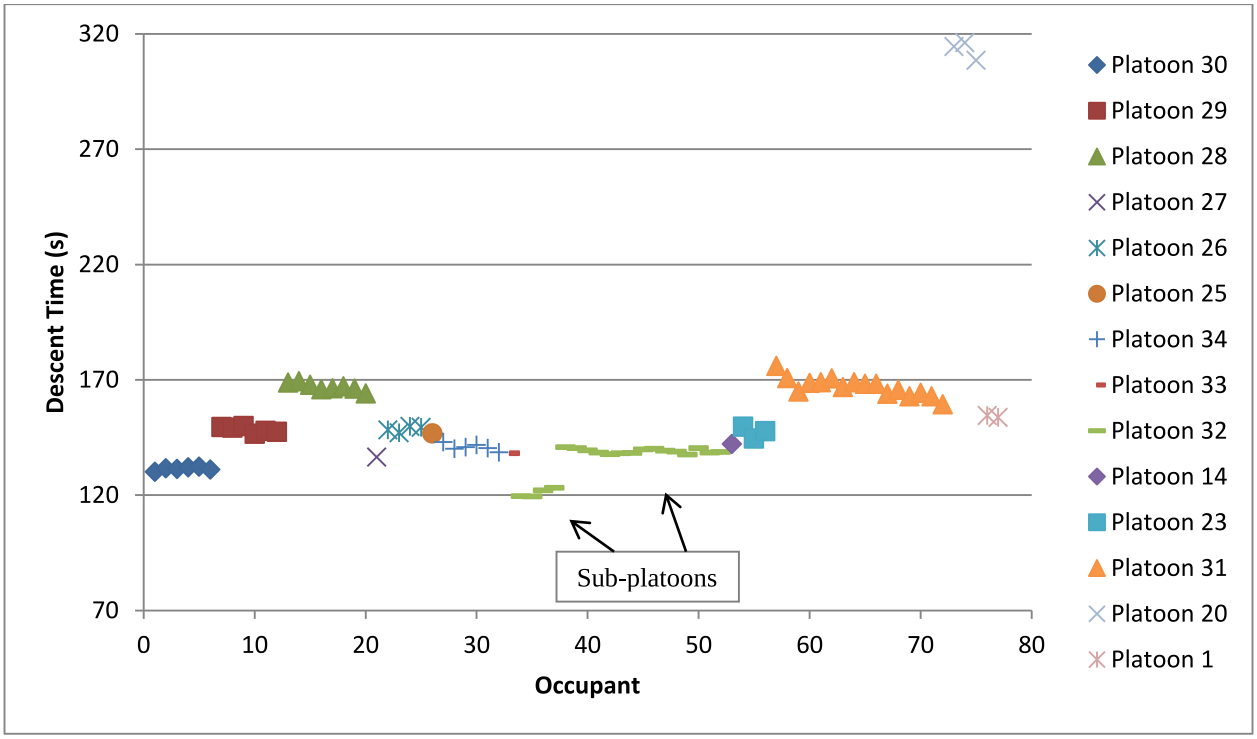


Figure 5-33: Stairwell 6_5 Platoon Descent Times from Floor 7 to 1

5.3.2 Stairwell 6_5A

Six platoons are identified exiting the camera view at floor 40. Figure 5-34 illustrates the descent times of the platoons from floor 40 to 34. All six platoons travel in equilibrium during this descent.

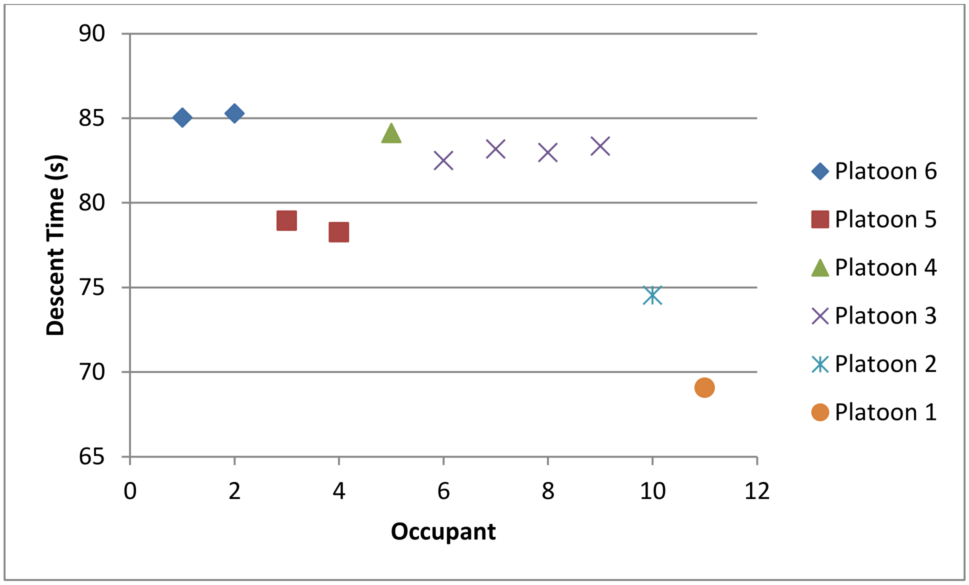


Figure 5-34: Stairwell 6_5A Platoon Descent Times from Floor 40 to 34

Figure 5-35 illustrates the descent times of the platoons from floor 34 to 26. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 34:

- Platoons 5 and 6 remain unchanged.
- Platoons 1 and 2 merge creating platoon 7.
- Platoons 3 and 4 merge creating platoon 8.
- One new platoon emerges, platoon 9.

During this descent, platoons 5, 6, 7, and 9 slightly travel in elongation while platoon 8 travels in equilibrium.

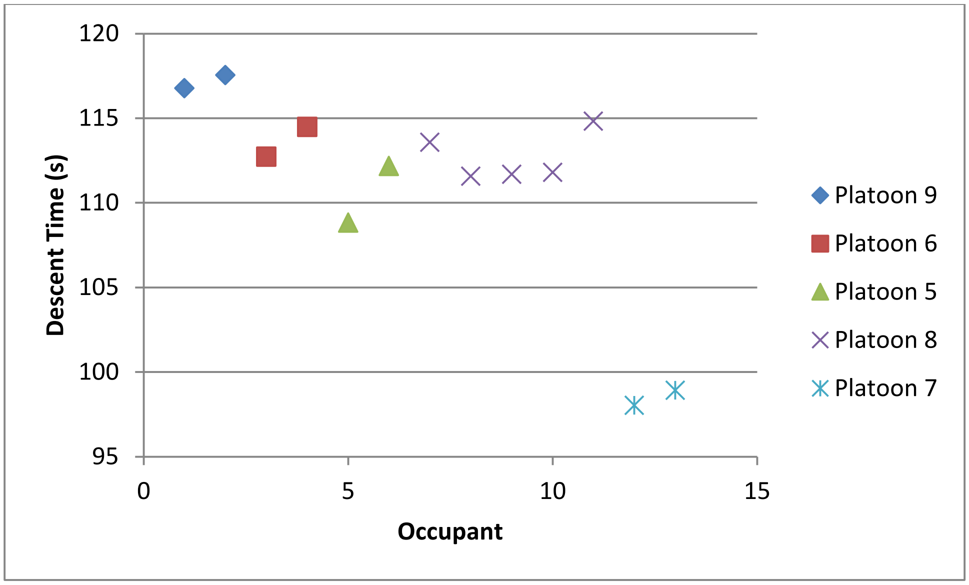


Figure 5-35: Stairwell 6_5A Platoon Descent Times from Floor 34 to 26

Figure 5-36 illustrates the descent times of the platoons from floor 26 to 12. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 26:

- Platoons 5, 6, 7, 8, and 9 remain unchanged.
- Six new platoons emerge, platoons 10-15.

During this descent, all of the platoons travel in equilibrium. At this point, the upper half of the camera views in stairwell 6_5A have been analyzed; therefore, no new platoons will be analyzed for the lower half.

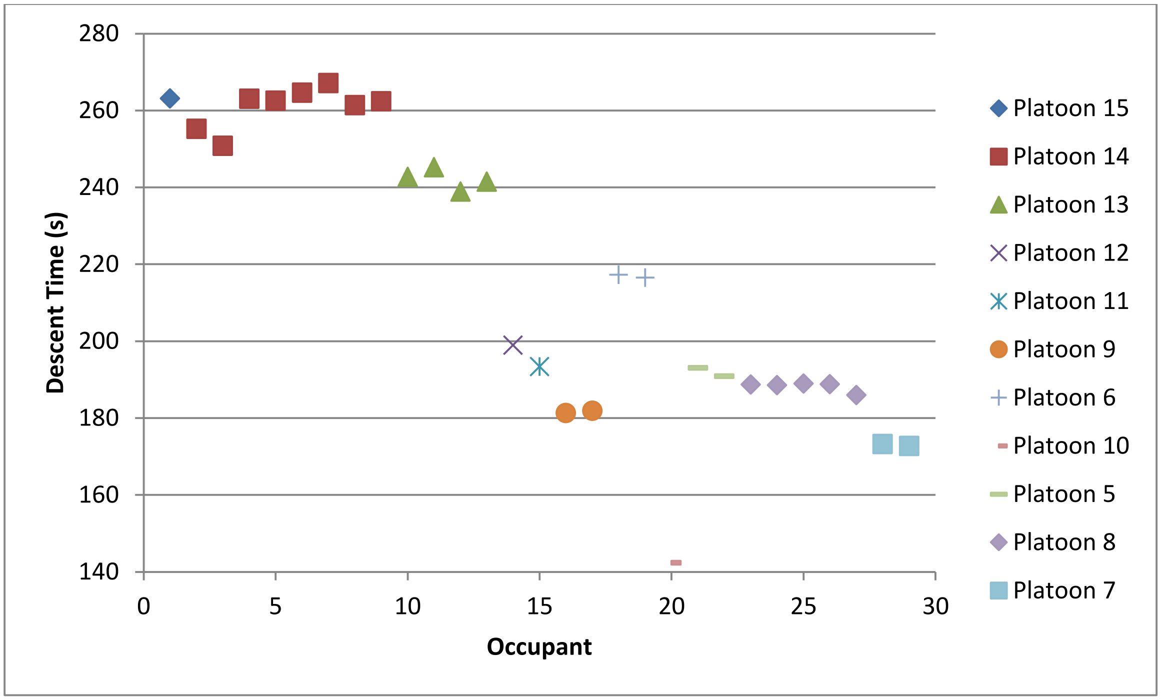


Figure 5-36: Stairwell 6_5A Platoon Descent Times from Floor 26 to 12

Figure 5-37 illustrates the descent times of the platoons from floor 12 to 7. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 12:

- Platoons 5, 6, and 10 remain unchanged.
- Platoons 7 and 8 merge creating platoon 16.
- Platoons 9 and 11 merge and add new occupants creating platoon 17.

Platoons 12, 13, 14, and 15 merge and add new occupants creating platoon 18.

During this descent, platoon 17 travels in compression and platoon 18 travels in elongation. All of the other platoons travel in equilibrium. Two sub-platoons are present in platoon18. The last sub-platoon of platoon 18 travels in elongation while the first travels in equilibrium.

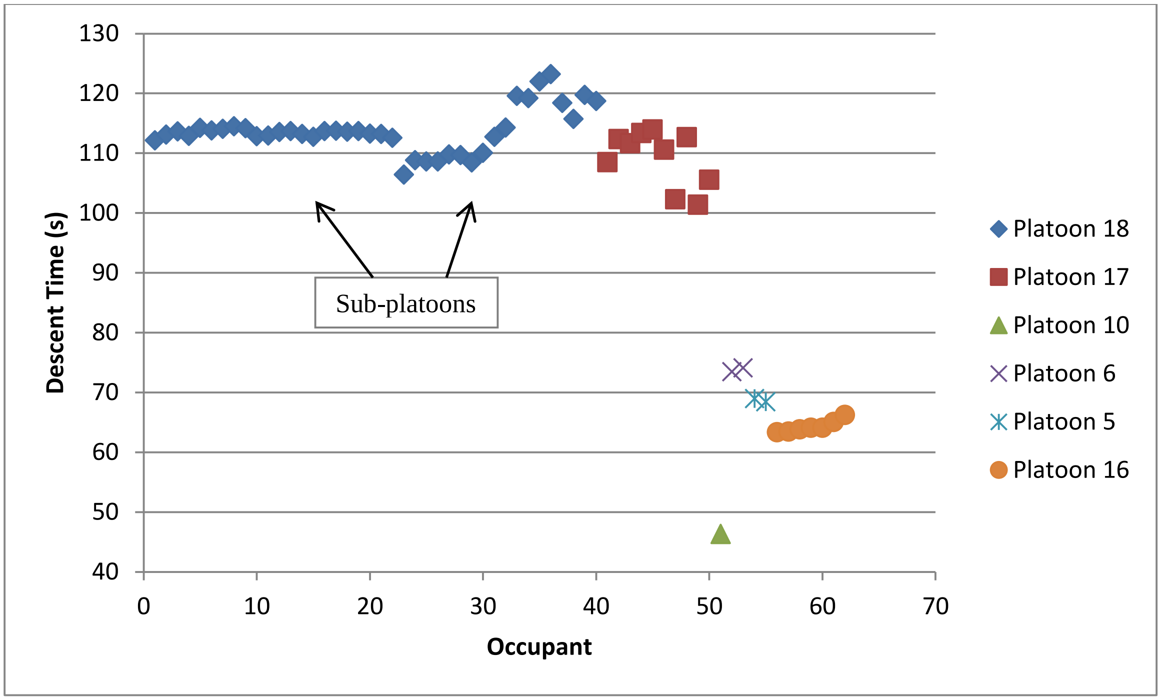


Figure 5-37: Stairwell 6_5A Platoon Descent Times from Floor 12 to 7

Figure 5-38 illustrates the final descent times of the platoons from floor 7 to 1. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 7:

- Platoons 5, 6, 10, and 16 remain unchanged.
- Platoon fragments creating platoons 19 and 20.
- Platoons 17 merges with platoon 20 and add new occupants.

During this descent, all of the platoons travel in equilibrium with the exception of platoon 20 which travels in elongation. Three sub-platoons are present in platoon 20, all of which travel in elongation. Also, platoon 19 is a one-person platoon which is continuously passed by the occupants in platoon 20.

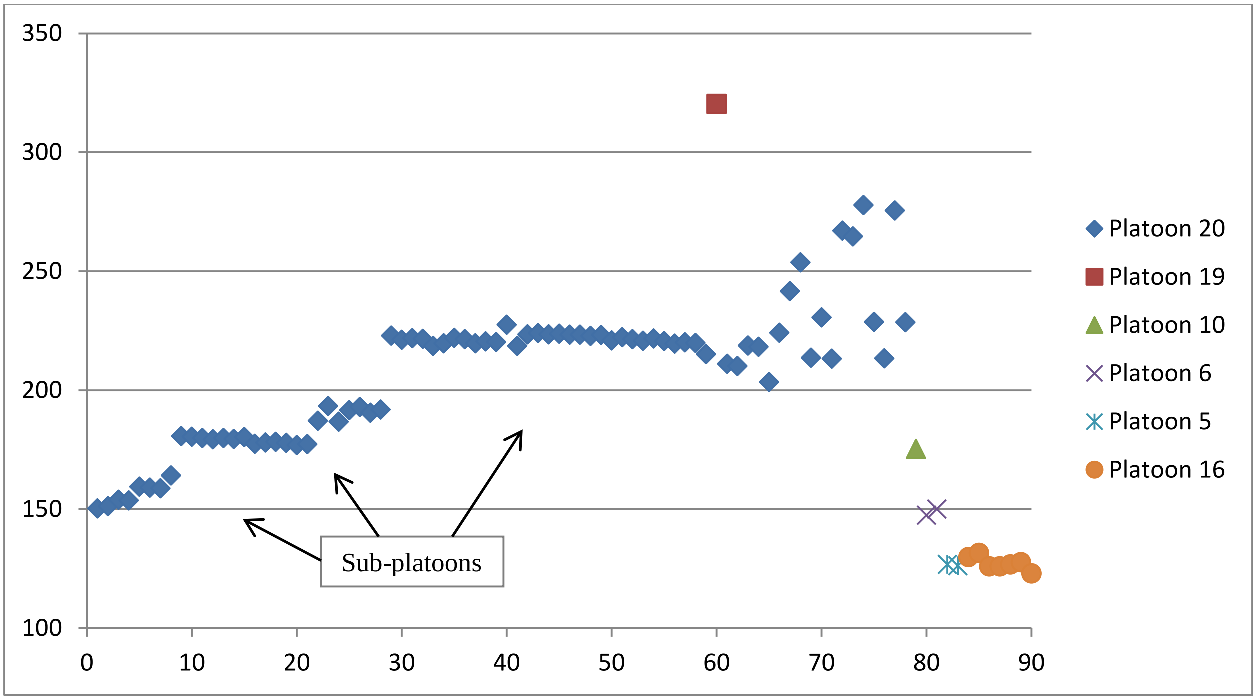


Figure 5-38: Stairwell 6_5A Platoon Descent Times from Floor 7 to 1

5.3.3 Discussion

The results of the platoon analysis for the two stairwells of Building 6 indicate similar trends as in Buildings 4 and 5. In multiple circumstances, platoons that elongated between camera views have fragmented. For example, in stairwell 6_5 platoons 11, 18, 19, and 24 all travel in elongation and fragment during their descent. Also, in stairwell 6_5A the second sub-platoon in platoon 18 travels in elongation and later fragments.

Conversely, the pattern of a platoon traveling in compression in some cases leads to a merge. For example, in stairwell 6_5 platoons 12 and 13 as well as the last sub-platoon of platoon 18 and platoon 17 have a trend of compression indicated with the greater descent time by each of these platoons as compared to the following platoon. Each of these platoons merges together during their descent. Also, in stairwell 6_5A, platoons 1 and 2, 7-9 and 11-15 have a trend of compression which leads to a merging of platoons. Furthermore, platoon 17 travels in compression and later merges with another platoon.

Again, as in Buildings 4 and 5, a trend exists where the last platoon to exit the stairwell remained unchanged. In stairwell 6_5, platoon 1 remained unchanged during its entire descent; however, this stairwell had the fewest amount of occupants and the longest distance to descend before reaching the exit floor. Conversely, platoon 6 remained unchanged during the entire descent of stairwell 6_5A, but this platoon was not the last to exit. Platoons 1-4 were last to exit the stairwell; however, they all merged together during their descent. Once these platoons merged together they remained unchanged during their final descent.

A total of 52 platoons were identified in stairwell 6_5. Neglecting the first descent from floor 44 to 36 because no changes could take place during this descent, 14 (28%) platoons remained unchanged, 6 (12%) added new occupants, 7 (14%) resulted in a merge, and 16 (32%) resulted in fragmentation out of 50 platoons. Therefore, the greatest number of platoons fragmented and the least amount added new occupants. Table 5-9 illustrates the changes occurring to the platoons in stairwell 6_5 as they descend from one camera view to the next.

	Number of Platoons						
Floor	Total	Unchanged	Added New Occupants	Merged	Fragmented	One-person	New
44 to 36	2					0	2
36 to 30	4	0	0	0	0	0	2
30 to 20	7	1	1	1	4	2	2
20 to 13	10	1	2	2	0	4	7
13 to 7	15	4	1	2	10	5	0
7 to 1	14	8	2	2	2	4	0

Table 5-9: Platoon Variations for Stairwell 6_5

Table 5-10 illustrates the associated sizes of the platoons for stairwell 6_5. Of the 52 platoons identified, platoons frequently consist of one-person and the least amount of platoons consists of 2 occupants.

Number of Occupants	Number of Platoons
1 Person	15 (28.8%)
2 Persons	7 (13.5%)
3-5 Persons	13 (25%)
6-10 Persons	9 (17.3%)
11+ Persons	8 (15.4%)
Total	52

Table 5-10: Platoon Sizes for Stairwell 6_5

A total of 34 platoons were identified in stairwell 6_5A. Neglecting the first descent from floor 40 to 34 because no changes could take place during this descent, 12 (42.9%) platoons remained unchanged, 3 (10.7%) added new occupants, 6 (21.4%) resulted in a merge, and 2 (7.1%) resulted in fragmentation out of 28 platoons. Therefore, the greatest number of platoons unchanged and the least amount resulted in fragmentation. Table 5-11 illustrates the changes occurring to the platoons in stairwell 6_5A as they descend from one camera view to the next.

	Number of Platoons						
Floor	Total	Unchanged	Added New Occupants	Merged	Fragmented	One-person	New
40 to 34	6					3	6
34 to 26	5	0	0	2	0	0	1
26 to 12	11	5	0	0	0	4	6
12 to 7	6	3	2	3	0	1	0
7 to 1	6	4	1	1	2	2	0

Table 5-11: Platoon Variations for Stairwell 6_5A

Table 5-12 illustrates the associated sizes of the platoons for stairwell 6_5A. Of the 34 platoons identified, platoons most frequently contain 2 occupants and the least amount of platoons contains 11 or more occupants.

Number of Occupants	Number of Platoons
1 Person	9 (26.5%)
2 Persons	15 (44.1%)
3-5 Persons	4 (11.8%)
6-10 Persons	4 (11.8%)
11+ Persons	2 (5.9%)
Total	34

Table 5-12: Platoon Sizes for Stairwell 6_5A

Overall both stairwells 6_5 and 6_5A are different in their patterns of platoon size and variation. Stairwell 6_5 frequently has one-person platoons and platoons that fragment. Conversely, stairwell 6_5A frequently has platoons containing two persons and platoons that remain unchanged.

5.4 Platoon Analysis of Building 7

The following section contains an analysis of the platoons identified in Building 7 using the methodology described in Section 4.3 and 4.4. All of the changes in the descent of the platoons for Building 7 are described in Section 5.4.3.

5.4.1 Stairwell 7_3

Thirteen platoons are identified exiting the camera view at floor 17. Figure 5-39 illustrates the descent times of the platoons from floor 17 to 15. All thirteen platoons travel in equilibrium during this descent. A queue has formed before platoon 5 reaches floor 15 indicated by the descent time more than tripling from platoon 13.

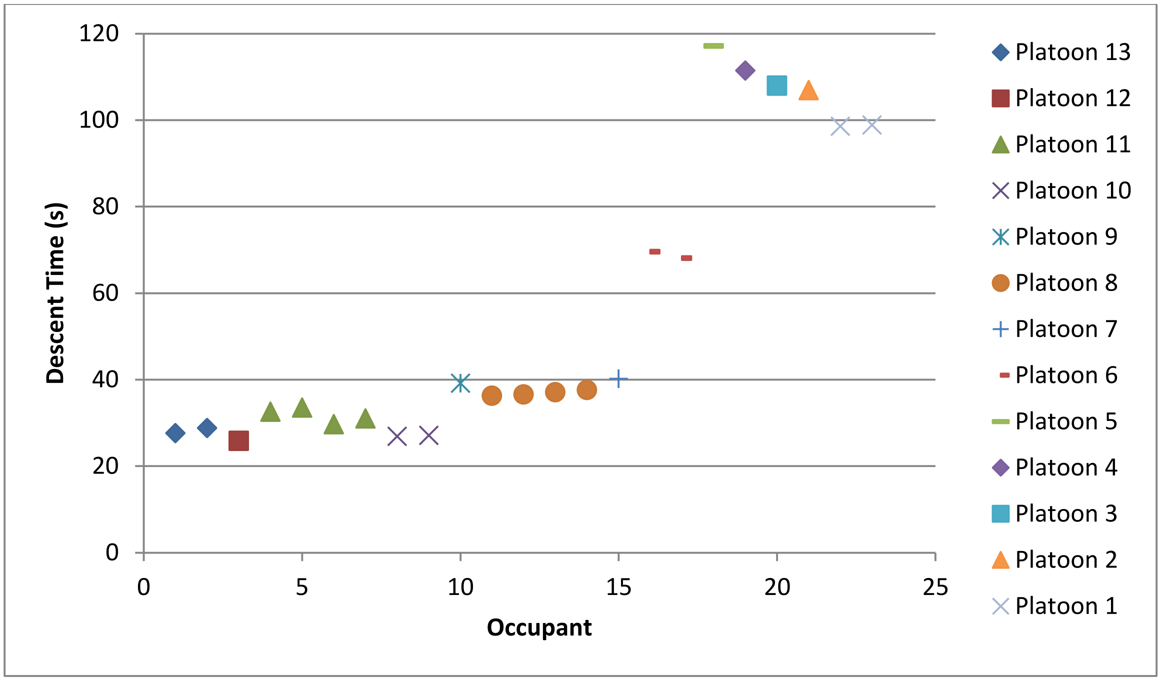


Figure 5-39: Stairwell 7_3 Platoon Descent Times from Floor 17 to 15

Figure 5-40 illustrates the descent times of the platoons from floor 15 to 13. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 15:

- Platoons 1-9 merge and add new occupants creating platoon 18.
- Platoons 10 and 11 merge and add new occupants creating platoon 20.
- Platoons 12 and 13 merge together creating platoon 21.
- Eight new platoons emerge, platoons 14, 15, 16, 17, 19, 22, 23, and 24.

During this descent, a queue is again present indicated by the increasing descent times starting in platoon 20 and peaking in platoon 18. Also, sub-platoons are present in platoons 18 and 20. Two sub-platoons exist in platoon 20, the first travels in equilibrium and the last elongates. Three sub-platoons exist in platoon 18, the first two elongate and the last travels in equilibrium. Overall, platoon 18 travels in compression and platoon 20 elongates. All other platoons travel in equilibrium.

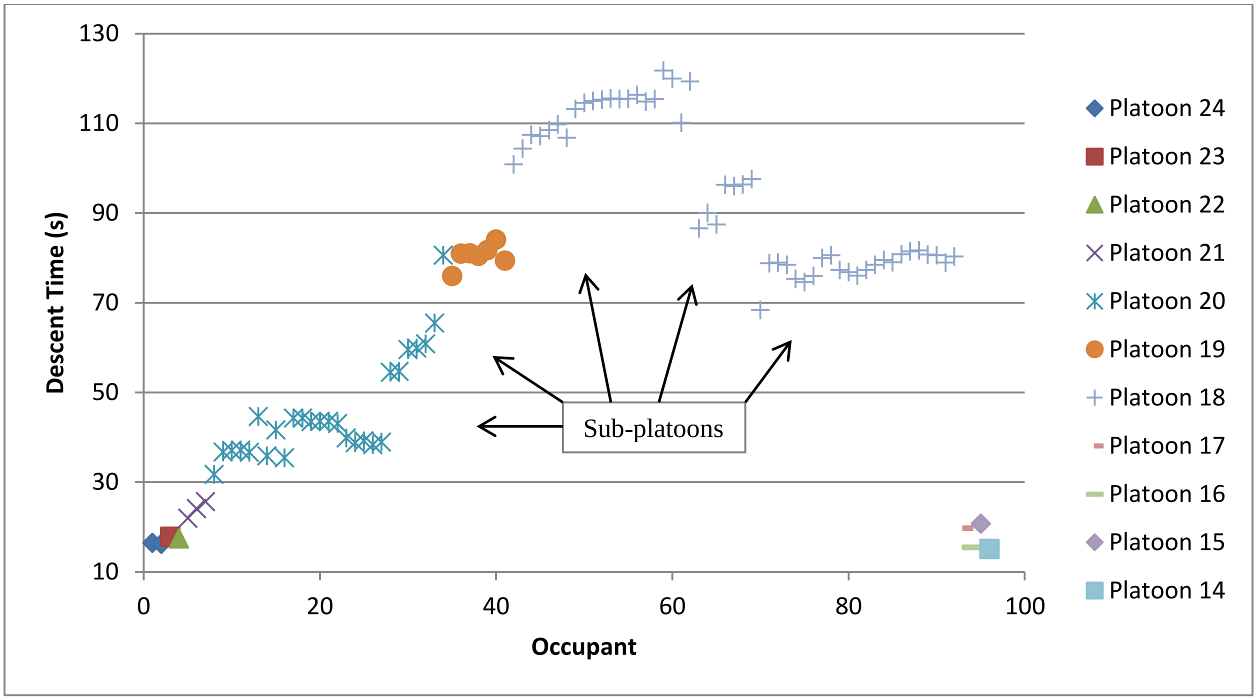


Figure 5-40: Stairwell 7_3 Platoon Descent Times from Floor 15 to 13

Figure 5-41 illustrates the descent times of the platoons from floor 13 to 11. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 13:

- Platoons 15, 16, 23, and 24 remain unchanged.
- Platoon 20 fragments creating platoons 26 and 27.
- Platoon 21 fragments creating platoons 27 and 28.
- Fragmented occupants from platoons 20 and 21 merge creating platoon 27.
- Platoons 18 and 19 merge with platoon 26.
- Platoons 14, 17, 22, 26, and 27 add new occupants.
- Two new platoons emerge, platoons 25 and 29.

During this descent, a queue is again present in platoon 26 indicated by the increasing descent times within the platoon. Platoon 26 has five sub-platoons. The first, second, and fourth sub-platoons travel in elongation, the third travels in compression, and the last travels in equilibrium. All of the other platoons travel in equilibrium with the exception of platoons 17 and 27, which elongate. Platoon 25 is a one-person platoon who is continuously passed by the occupants in platoons 16 and 17 before exiting the camera view at floor 11.

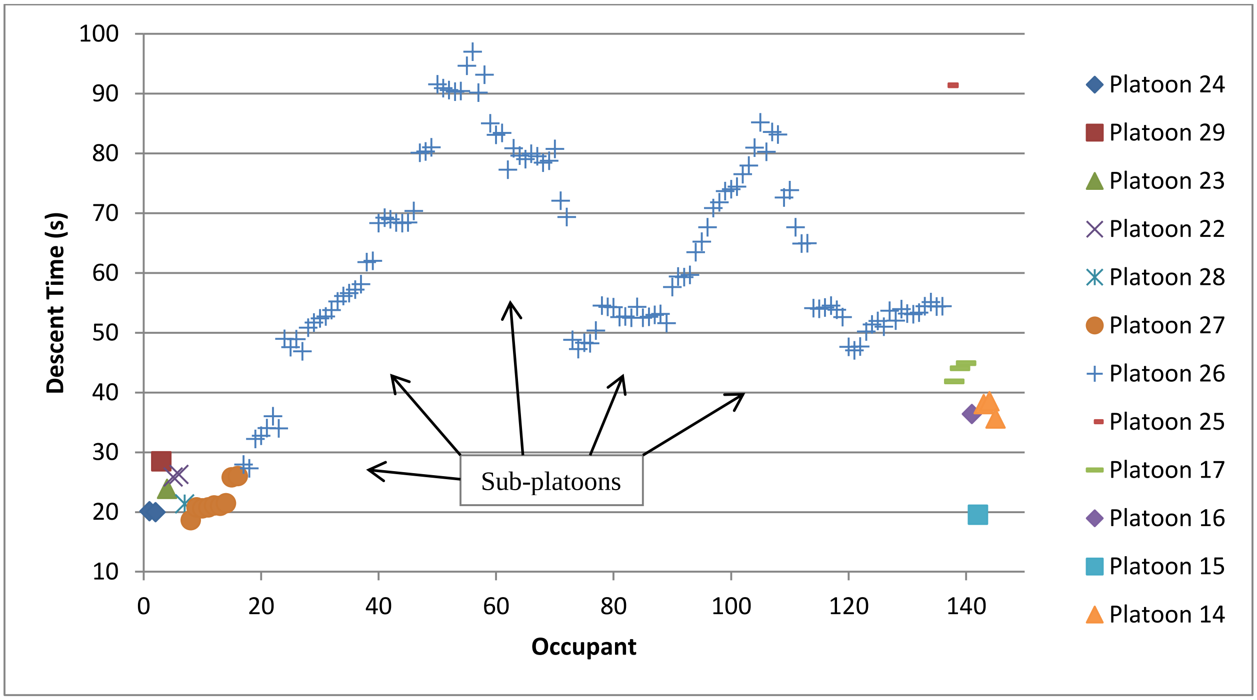


Figure 5-41: Stairwell 7_3 Platoon Descent Times from Floor 13 to 11

Figure 5-42 illustrates the descent times of the platoons from floor 11 to 9. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 11:

- Platoons 14, 15, and 25 remain unchanged.
- Platoon 17 fragments creating platoons 30 and 31.
- Platoon 27 fragments creating platoons 31 and 32.
- Platoon 24 fragments creating platoons 34 and 35.
- Platoons 16 and 26 merge with platoon 31.

- Platoon 28 merges with platoon 32.
- Platoons 22, 23, and 29 merge creating platoon 33.
- Platoons 31, 32, 33, 34, and 35 add new occupants.

During this descent platoons 32, 33, and 34 travel in elongation while platoon 31 travels in compression. Also, platoons 25 and 30 slow their descent before exiting the camera view at floor 9 indicated by the increased descent times compared to the descent times in platoon 31. At this point, the upper half of the camera views in stairwell 7_3 have been analyzed; therefore, no new platoons will be analyzed for the lower half.

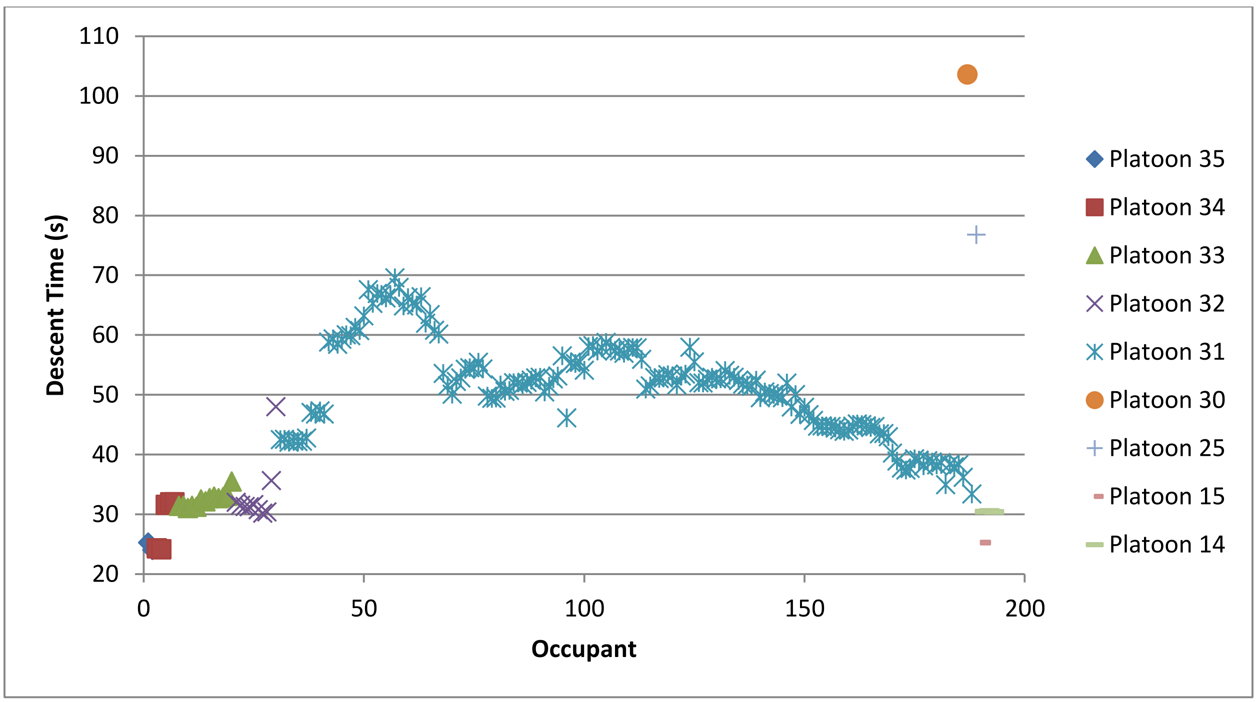


Figure 5-42: Stairwell 7_3 Platoon Descent Times from Floor 11 to 9

Figure 5-43 illustrates the descent times of the platoons from floor 9 to 7. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 9:

- Platoons 15, 25, and 30 remain unchanged.
- Platoon 14 fragments creating platoons 36 and 37.

- Platoon 31 fragments creating platoons 38 and 39.
- Platoon 35 fragments creating platoons 39 and 40.
- Platoons 32, 33, and 34 merge with platoon 39.
- Platoons 38, 39, and 40 add new occupants.

During this descent, platoons 39 and 40 travel in elongation while platoon 38 travels in compression. Also, five sub-platoons are present in platoon 39 and two sub-platoons are present in platoon 40. All of the sub-platoons travel in equilibrium with the exception of the first two sub-platoons in platoon 39 which travels in elongation. During this descent, platoons 25 and 30 have again slowed their descent and are passed by platoon 15 before exiting the camera view at floor 7.

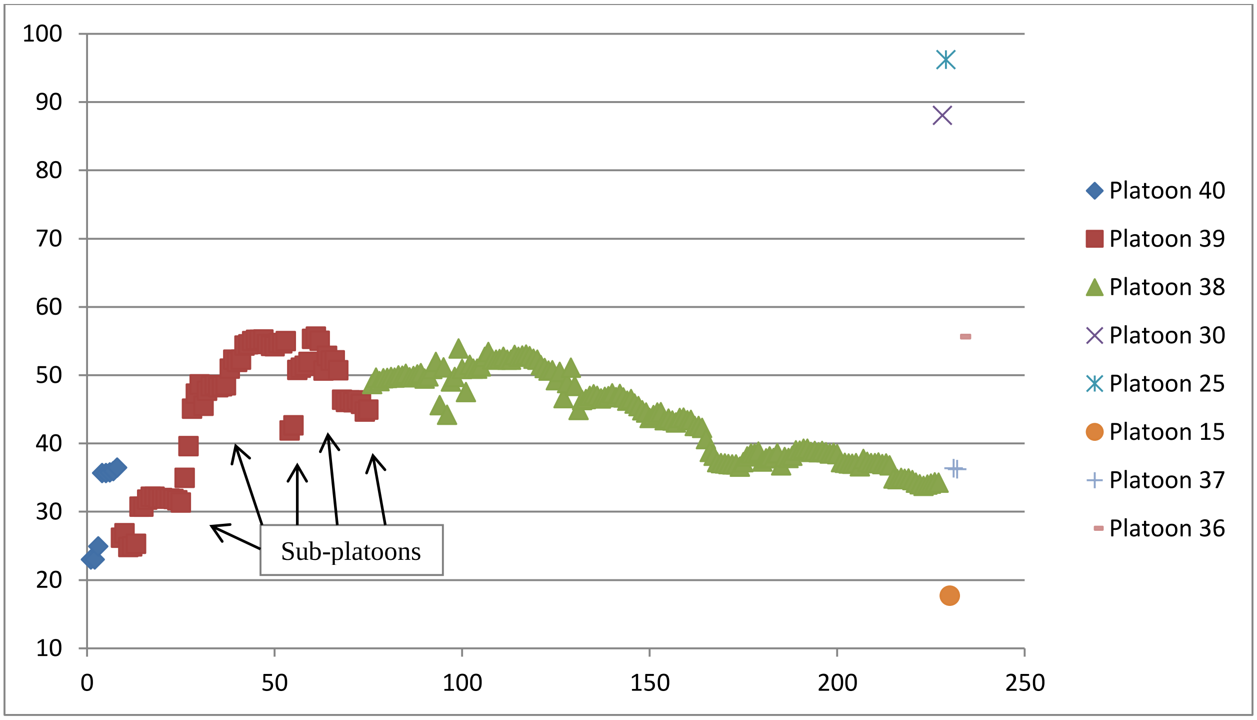


Figure 5-43: Stairwell 7_3 Platoon Descent Times from Floor 9 to 7

Figure 5-44 illustrates the final descent times of the platoons from floor 7 to 5. The following list describes the changes for the platoons as they are seen exiting the camera view at floor 7:

- Platoons 15, 25, 30, and 36 remain unchanged.
- Platoon 39 fragments creating platoons 41 and 42.
- Platoons 37, 38, 40, and 41 add new occupants.

During this descent, platoon 38 travels in compression while platoon 40 travels in elongation. All other platoons travel in equilibrium. Also, three sub-platoons are present in platoon 40, all of which travel in elongation. During this descent, platoons 25, 30, and 36 slow their descent indicated by the high descent times compared to the occupants in the nearby platoons. Also, one occupant in the beginning of platoon 38 slows their descent indicated by the descent time 20 seconds higher than the nearby occupants.

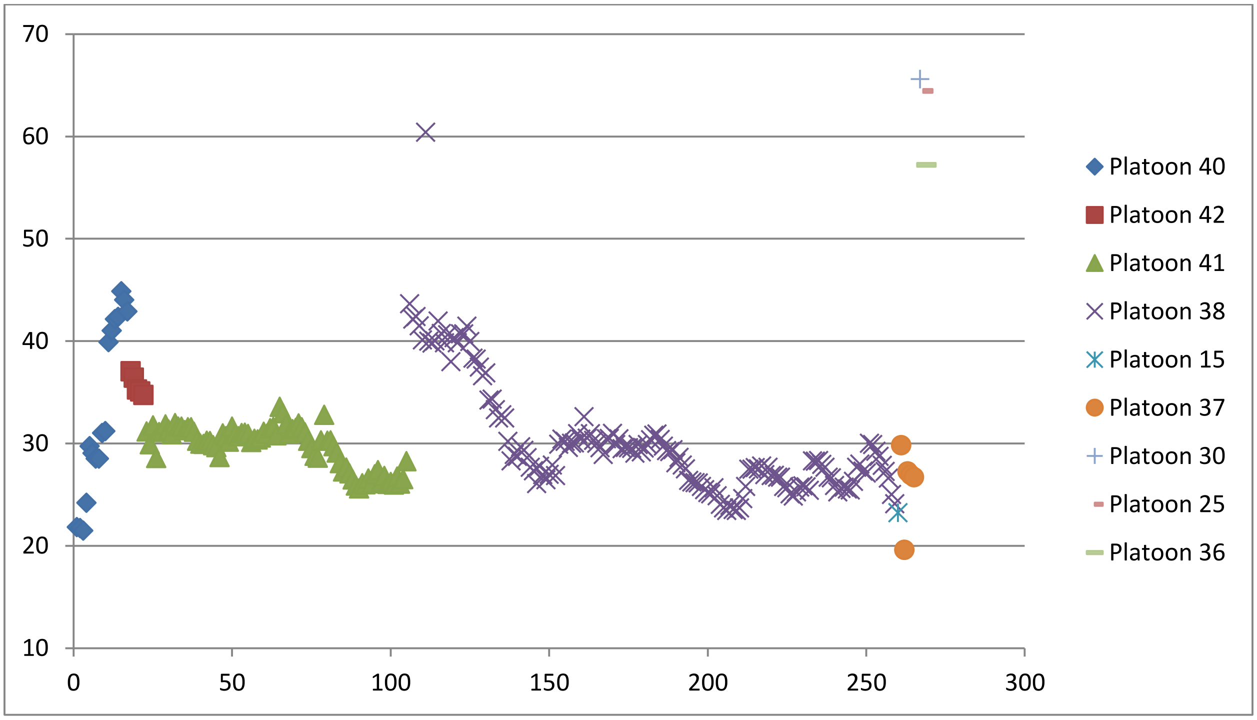


Figure 5-44: Stairwell 7_3 Platoon Descent Times from Floor 7 to 5

5.4.2 Discussion

The results of the platoon analysis for Building 7 indicate similar trends again as in Buildings 4, 5, and 6. In many circumstances, platoons that elongated during a descent of two floors have fragmented. For example, platoons 17, 20, 21, 27, and 39 all travel in elongation and fragment during their descent. Also, the initial occupants of platoon 31 travel in elongation and later fragment.

Conversely, the pattern of a platoon traveling in compression in some cases leads to a merge. For example, platoons 1-5 from floor 17 to 15 and platoons 22, 23, 28, and 29 from floor 13 to11 have a trend of compression as each platoon has a higher descent time than the following platoon. Each of these platoons merges together during their descent. Also, platoon 18 travels in compression and later merges with other platoons.

Again, as in Buildings 4, 5, and 6, a trend exists where the final platoons to exit the stairwell remained unchanged. In stairwell 7_3, platoons 15 and 25 remained unchanged during their entire descent, but these platoons were not the last to exit. These platoons waited more than 7 minutes to begin their evacuation, which allowed for a less crowded stairwell and time for queues to dissipate.

A total of 62 platoons were identified in stairwell 7_3. Neglecting the first descent from floor 17 to 15 because no changes could take place during this descent, 14 (28.6%) platoons remained unchanged, 19 (38.8%) added new occupants, 9 (18.4%) resulted in a merge, and 12 (24.5%) resulted in fragmentation out of 49 platoons. Therefore, the greatest number of platoons added new occupants and the least amount resulted in a merge. Table 5-13 illustrates the changes occurring to the platoons in stairwell 7_3 as they descend from one camera view to the next.

	Number of Platoons						
Floor	Total	Unchanged	Added New Occupants	Merged	Fragmented	One-person	New
17 to 15	13					7	13
15 to 13	11	0	2	3	0	6	8
13 to 11	12	4	5	2	3	6	2
11 to 9	9	3	5	3	4	3	0
9 to 7	8	3	3	1	3	4	0
7 to 5	9	4	4	0	2	4	0

Table 5-13: Platoon Variations for Stairwell 7_3

Table 5-14 illustrates the associated sizes of the platoons for stairwell 7_3. Of the 62 platoons identified, the greatest number of platoons consists of one-person and the least amount of platoons consists of 6-10 occupants.

Number of Occupants	Number of Platoons
1 Person	30 (48.4%)
2 Persons	9 (14.5%)
3-5 Persons	9 (14.5%)
6-10 Persons	4 (6.5%)
11+ Persons	10 (16.1%)
Total	62

Table 5-14: Platoon Sizes for Stairwell 7_3

5.5 Platoon Analysis for All Seven Stairwells

5.5.1 Platoon Variations

Neglecting the first descent of all seven stairwells, a total of 331 platoons were identified. For the platoons identified in the seven stairwells, 3 stairwells had platoons frequently remaining unchanged, 3 had platoons frequently fragmenting, and 1 had a frequent occurrence of adding new occupants. The analysis of all seven stairwells resulted in 32.3% of the platoons remaining unchanged, 23.6% adding new occupants, 16% merging, and 23.3% fragmenting. Therefore, across all four Buildings, platoons most frequently remained unchanged and the least amount resulted in a merge between camera views. These results are illustrated in Table 5-15.

Number of Platoons				
Total (Neglecting First Descent)	Unchanged	Added New Occupants	Merged	Fragmented
331	107 (32.2%)	78 (23.6%)	53 (16%)	77 (23.3%)

Table 5-15: Platoon Variations for All Seven Stairwells

The results of the platoon variations partially agree with the variations reported by Galea and Blake [18] on groups in the WTC evacuations. Galea and Blake reported that 40% and 20% of the groups in WTC1 and WTC2 remained intact and 60% and 25% of the groups in WTC1 and WTC2 fragmented either intentionally or unintentionally. Although the percentage of groups that remained intact in the WTC evacuations was near the 32.3% reported in this research, the majority of the groups in the WTC evacuations resulted in fragmentation. However, the reported data from the WTC evacuations was collected from literature published in the public domain and only included a total of 260 occupants. The platoons analyzed in this study were identified from video cameras within the stairwells and consisted of more than 1500 occupants. Furthermore, the platoons analyzed from the NIST data participated in fire drills with no loss of life compared to the many deaths of occupants during the WTC evacuations.

5.5.2 Platoon Size

In the analysis of the four buildings, all of the stairwells with the exception of stairwell 6_5A had platoons most frequently consisting of one-person. Also, four out of seven of the stairwells had the least amount of platoons contain 6-10 occupants. These results are reflected across all seven stairwells. Out of the 385 identified platoons, 151 were one-person platoons and only 38 platoons contained between 6-10 occupants. The sizes of the platoons for all seven stairwells are illustrated in Table 5-16.

Number of Occupants	Number of Platoons
1 Person	151 (39.2%)
2 Persons	80 (20.8%)
3-5 Persons	53 (13.8%)
6-10 Persons	38 (9.9%)
11+ Persons	63 (16.4%)
Total	385

Table 5-16: Platoon Sizes for All Seven Stairwells

The results of the size of platoons analyzed surprising agree with the social groups identified by Proulx [14] in her study of evacuations from apartment buildings. Proulx concluded that 62% of the occupants evacuated in groups and 38% evacuated alone. These percentages compare well to the 60.8% of platoons that had two or more occupants and the 39.2% one-person platoons found in this research. However, Proulx observed an evacuation of a residential high-rise building which was different from the high-rise office building evacuation data used in this research. Also, no social groups could be identified from the data used in this research compared to the family groups observed by Proulx.

Conversely, the sizes of the platoons analyzed do not agree with the sizes of the platoons reported by Galea and Blake [18] from the WTC evacuations. Galea and Blake reported that 90% and 88% of the occupants from WTC1 and WTC2 evacuated in platoons. However, the reported percentages did not consist of the entire population evacuating from the WTC buildings and was composed of literature published in the public domain.

Furthermore, the results of the platoon sizes are very different compared to the groups recorded by Proulx [17] in the Cook County Administration Building Fire. Proulx noted that the groups frequently contained 3-5 persons and least amount of groups contained 11 or more occupants. However, the results reported by Proulx were collected from surveys sent to occupants who evacuated the building the day of that fire and only included a 40% return rate.

Furthermore, Proulx's recordings only accounted for the size of the groups when the occupants began their evacuation and did not contain information on whether the group was a social group or a platoon.

Finally, by viewing each of the descent plots from all seven stairwells a qualitative trend exists where the larger platoons travel the slowest in non-queued conditions. For example, in the final descent plot for stairwell 5B (Figure 5-27), platoons 10, 26, and 28 are the smallest platoons and descend the stairs faster than platoons 29 and 30. This qualitative comparison is similar to the pedestrian platoons studied by Gates et al. where a longer time was needed to cross an intersection for larger platoons [24]. Therefore, Gates et al. concluded that larger platoons travel slower than smaller platoons.

5.6 Platoon Analysis of Pathfinder Egress Model

After analyzing the platoons from the empirical egress data collected by NIST, a qualitative analysis of the Pathfinder egress model is conducted to determine if platoons exist in a current model. Pathfinder 2011 is chosen for this analysis for several reasons. First, this computer egress model is publicly available and allows for a free 30-day trial. Second, Pathfinder is verified to ensure the model is performing as specified [4]. Third, Pathfinder is validated against several International Maritime Organization (IMO) tests to ensure the model simulates the behavior of people movement [4]. Fourth, Pathfinder incorporates a 3D movement viewer which is essential in identifying platoons qualitatively. Finally, Pathfinder is a current agent-based model which could be capable of simulating platoons.

Two simple geometries were created in Pathfinder for the platoon analysis. The first geometry was a 4-story building with floors 2, 3, and 4 having occupants and floor 1 being the exit floor. The second geometry was a 10-story building with floors 2-10 having occupants and floor 1 being the exit floor. One stairwell connected the floors for both geometries. This stairwell was constructed using the dimensions of the stairs in Building 5. The stairs were 1.27 meters wide and the individual steps measured 0.18 m rise and 0.28 m tread depth. The stairs between floors had 11 steps leading to a 1.27 by 2.54 m landing and another 11 steps leading to an identical landing on the floor level. The exit door and the doors connecting each floor to the stairwell were 1 m wide. The 4 and 10 story geometries are illustrated in Figure 5-45.

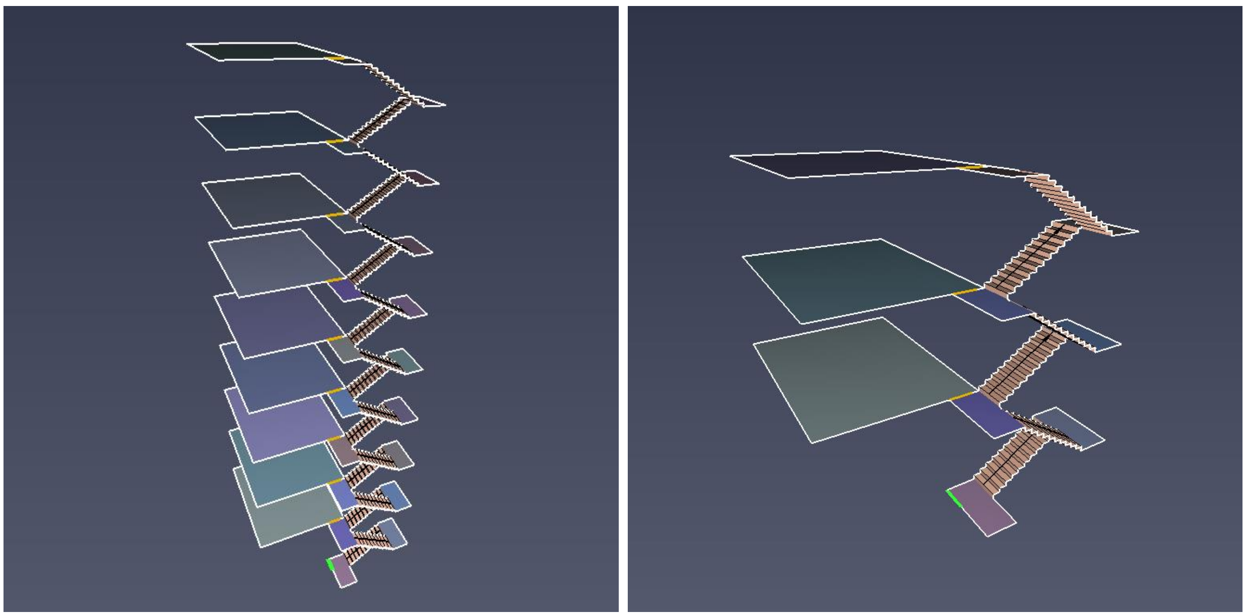


Figure 5-45: Pathfinder Geometries: 10 Floors (Left) and 4 Floors (Right)

Each floor contained a 6.5 by 8 m room where occupants were distributed randomly for each simulation. It was determined by trial and error that having 20 occupants per floor contained little queuing situations and having 40 occupants per floor generated a large queue as seen in Buildings 4, 5, and 7. For the 4 floor geometry, 20 and 40 occupants were placed randomly on the top three floors making 60 and 120 occupants for the building. For the 10 floor geometry, 20 and 40 occupants were placed randomly on the top 5 floors making 100 and 200 occupants. Occupants were only placed on the top 5 floors for the 10 floor geometry because platoons were only identified for the upper half of the camera views for the empirical stairwells analyzed. Each one of the occupants was prescribed a random walking speed between 0.3 and 1.2 m/s to include a wide range of basic movement speeds down stairs [7].

Each one of the geometries with the two different occupant loads was run with both the SFPE and Steering modes in Pathfinder making a total of 8 simulations. The results of the Pathfinder simulations are shown in Table 5-17.

Mode	Geometry	Number of Total Occupants	Platoons Identified?	Passing?
SFPE	4 Floors	60	Yes	No
		120	Yes	No
	10 Floors	100	Yes	No
		200	Yes	No
Steering	4 Floors	60	Yes	Yes
		120	Yes	Yes
	10 Floors	100	Yes	Yes
		200	Yes	Yes

Table 5-17: Platoon Results for Pathfinder Simulations

For every Pathfinder simulation, platoons were qualitatively identified. In SFPE mode, occupants followed the basic hydraulic model and did not pass each other in the stairwell. Conversely, in steering mode, occupants with higher walking speeds passed those with slower walking speeds on most occasions. In some circumstances in steering mode, a slower occupant walked in the center of the stairwell and other occupants behind were unable to pass.

The platoon analysis in Pathfinder revealed that first-person follower platoons are created in SFPE mode and both first-person follower platoons and passing platoons are created in steering mode. First-person follower platoons are created when a slow occupant sets the pace for a number of occupants that are unable to pass the first occupant. These first-person follower platoons are identical to the platoons described by Hoskins [30] and the platoons of cars described by Shiomi et al. [28]. Hoskins noted in his research that most frequently the first person set the pace for a platoon which is identical to the platoons in SFPE mode. Shiomi et al.

found that a platoon of cars would form when a slow moving vehicle held back faster moving vehicles on a single-lane highway [28]. The faster moving vehicles could not pass the slow moving vehicle which is identical to how the faster moving occupants cannot pass the slower occupants in SFPE mode. Conversely, passing platoons are simply created when one or more occupants pass one or more slower occupants. An example of first-person follower platoons as seen in SFPE mode is illustrated in Figure 5-46 and an example of passing platoons is illustrated in Figure 5-47.

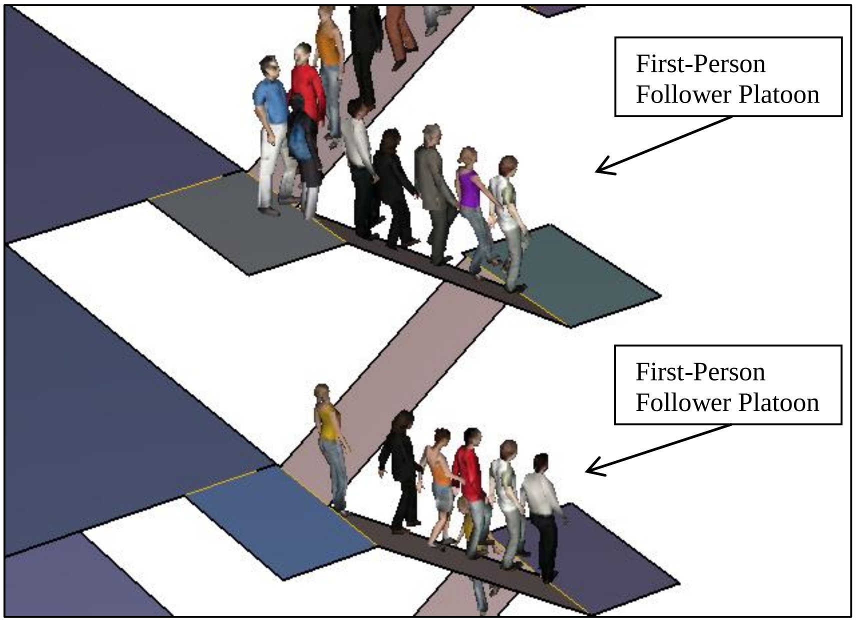


Figure 5-46: First-Person Follower Platoons in SFPE Mode

In Figure 5-46, two examples of first-person follower platoons are illustrated as a slow occupant sets the pace for the platoon. In Figure 5-47, the lady in front of the platoon (on the left) is passed by two men (on the right). This occupant is a one-person platoon which is continously passed by other occupants before exiting the building.

Figure 5-47: Passing Platoons in Steering Mode

Based upon the qualitative results of the Pathfinder simulations, several comparisons exist with the platoons from the platoons analyzed. First, the first-person follower platoons in both the SFPE and steering modes portray platoons seen in Building 4. Many platoons in Building 4 involved very little passing and each occupant followed the one in front towards the exit. However, Building 4 contained safety officers that told occupants to stay to the right during the evacuation which created the non-passing conditions. Also in SFPE mode, the majority of the platoons remain unchanged during their descent down the stairwell, which is the case for the empirical platoons analyzed. Furthermore in steering mode, the passing platoons viewed portray similar passing platoons seen primarily in Building 5. Many occupants in the Pathfinder model under steering mode pass others or are passed by others which is very similar to the high number of passing events in Building 5. Finally, in all Pathfinder simulations, large spatial separations existed between some occupants which are similar to the large exit time gaps greater than 10 seconds between some occupants in all four buildings. These spatial separations are the basis for which platoons were identified.

Even though comparisons can be made between the empirical data and the Pathfinder simulations, some discrepancies exist indicating that the computer model is inaccurate in replicating platoon behavior. For example, in SFPE mode, passing platoons do not exist which is unrealistic in the evacuation of high-rise stairwells. In all four buildings analyzed, passing events occurred among occupants either in the same or separate platoons in every stairwell. Also in steering mode, very few platoons remain unchanged as they travel down the stairwell. Multiple passing events occur which leads to large amount of platoon fragmentation and merges. This does not match the empirical platoons analyzed because the platoons across all seven stairwells most frequently remain unchanged during their descent between camera views.

Although platoons were identified in the agent-based model Pathfinder, it is possible that platoons may be identified in other computer egress models such as flow-based models and fine-network models. Flow-based models operate under the hydraulic model and assume every occupant has the same speed and passing would not occur. The condition of no passing occurring is similar to SFPE mode; however, for the qualitative platoon analysis the occupants had different walking speeds. Therefore, in flow-based models platoons would not be identified. In a flow-based simulation all occupants would enter a stairwell and proceed single-file walking down at the same speed. This would create one long platoon of occupants traveling down at the same speed.

In a fine-network model, occupants can only occupy a specified node (i.e. 0.5 by 0.5 meter space) and only move to a nearby node. This is different to the agent-based model where occupants have a range of body sizes which occupy their space in the egress mesh and can move in any direction. Unlike the flow-based model, occupants can have a range of walking speeds in the fine-network model. Therefore, mostly first-person follower platoons would be expected with very little passing within a platoon. For example, if a stairwell was 1.27 m wide, then in a fine-network model there would only be two 0.5 m nodes creating two lanes. Therefore, passing platoons would be expected in one of the two lanes. However, the slower occupants would create first-person follower platoons in both lanes.

A final comparison can be made between the four simulations in both SFPE and steering modes. The total egress time was longer for each of the simulations in SFPE mode compared to those in steering mode. This could indicate that passing during an evacuation leads to a more efficient egress time.

Chapter 6: Conclusions and Future Research

6.1 Platoon Behavior

Platoons are defined as a group of individuals that are spatially close to each other. However, platoons are identified based upon how they travel and if passing occurs over multiple floors. Three types of platoon movement are identified within the stairwell: platoon elongation, compression, and equilibrium. Platoon elongation occurs when the descent times between individuals within a platoon increase from one person to the next. Platoon compression occurs when the descent times between individuals within a platoon decrease from one person to the next. Finally, platoon equilibrium occurs when the descent times for the occupants within a platoon remain the same.

The results of the platoon analysis across the seven stairwells reveal a fairly consistent trend in patterns of platoon elongation leading to fragmentation and platoon compression leading to a merging of platoons. In many circumstances, when a platoon elongates during a descent between two camera views, it has fragmented before reaching the lower camera. Typically, this is expected under non-queued conditions because the beginning occupants are descending faster than the final occupants of the platoon. Likewise, in many circumstances when several platoons travel in compression during their descent between two camera views, they have merged together before reaching the lower camera. This is expected under both queued and non-queued conditions because the beginning platoons are travelling slower than the platoons behind. The patterns in which a platoon travels provides an understanding in how a platoon changes. This is important in understanding how the size of a platoon is created. If platoons travel in compression and merge together, then the platoon size will increase. Conversely, if a platoon travels in elongation and fragments, then smaller platoons will be created.

As a platoon descends a stairwell, its size can either increase, decrease, or remain unchanged. A platoon's size can increase by either adding new occupants to the platoon or merging with one or more other platoons. A platoon's size can decrease only by undergoing fragmentation when one or more occupants split apart from the platoon. The results of this platoon analysis show that platoons most frequently remain unchanged and the least amount result in a merge as they descend between camera views. Furthermore, out of the 385 identified platoons in this research, 151 are one-person platoons, 80 contain two occupants, 53 contain between 3-5 occupants, 38 contain between 6-10 occupants, and 63 contain 11 or more occupants. Therefore, platoons most frequently consist of one-person platoons and the least amount consists of 6-10 occupants. The quantitative results of the platoon analysis can be used to improve agent-based computer egress models. These models can be developed to account for a higher frequency of one-person platoons and platoons that remained unchanged during their descent.

Furthermore, a qualitative comparison exists as noted by Gates et al. [24] where larger platoons travel the slowest. Therefore, the slowest member of the larger platoons will dictate the speed, which is typically the leader as noted by Hoskins [30]. This provides an understanding to how platoons impact the total evacuation time of a building. For example, larger platoons will lead to longer evacuation times. This is important for developing methods to more accurately quantify a total egress time of a high-rise building.

The results of the qualitative platoon analysis from the Pathfinder egress simulations reveal that platoons are identified based on spatial separation in both SFPE and steering modes. In SFPE mode, first-person follower platoons are identified similar to the platoons identified by Hoskins [30] and the car following platoons identified by Shiomi et al. [28]. These platoons follow the slowest occupant and passing does not occur. Conversely, in steering mode, both passing platoons and first-person follower platoons are identified. However, very few platoons remain unchanged as they travel down the stairwell in steering mode. In comparing the platoons identified in SFPE and steering modes to the empirical platoons analyzed, steering mode provides a more realistic representation of the empirical platoons because passing occurs often in all of the stairwells analyzed. Therefore, the model can be improved to more accurately simulate egress behavior by incorporating the quantitative results from the platoon analysis.

6.2 Future Research

Very little data has been collected in the field of egress and human behavior in buildings and stairwells. Therefore, in order to better understand egress within stairwells, future evacuation studies need to be conducted with more emphasis on how platoons form. These future studies should capture human movement in the building as well as the entrance to the stairwell. Cameras should be placed within the building and near the exit doors to the stairwells. This would capture groups of occupants entering the stairwell and the associated changes occurring if they merge with other platoons. Furthermore, by viewing the egress from each floor and the entrance to the stairwell, platoons may be identified based on social groups rather than solely based upon spatial separation and movement within a stairwell. Conducting a study with cameras within the building may provide an understanding of why the phenomenon of platooning occurs and which platoons are social groups.

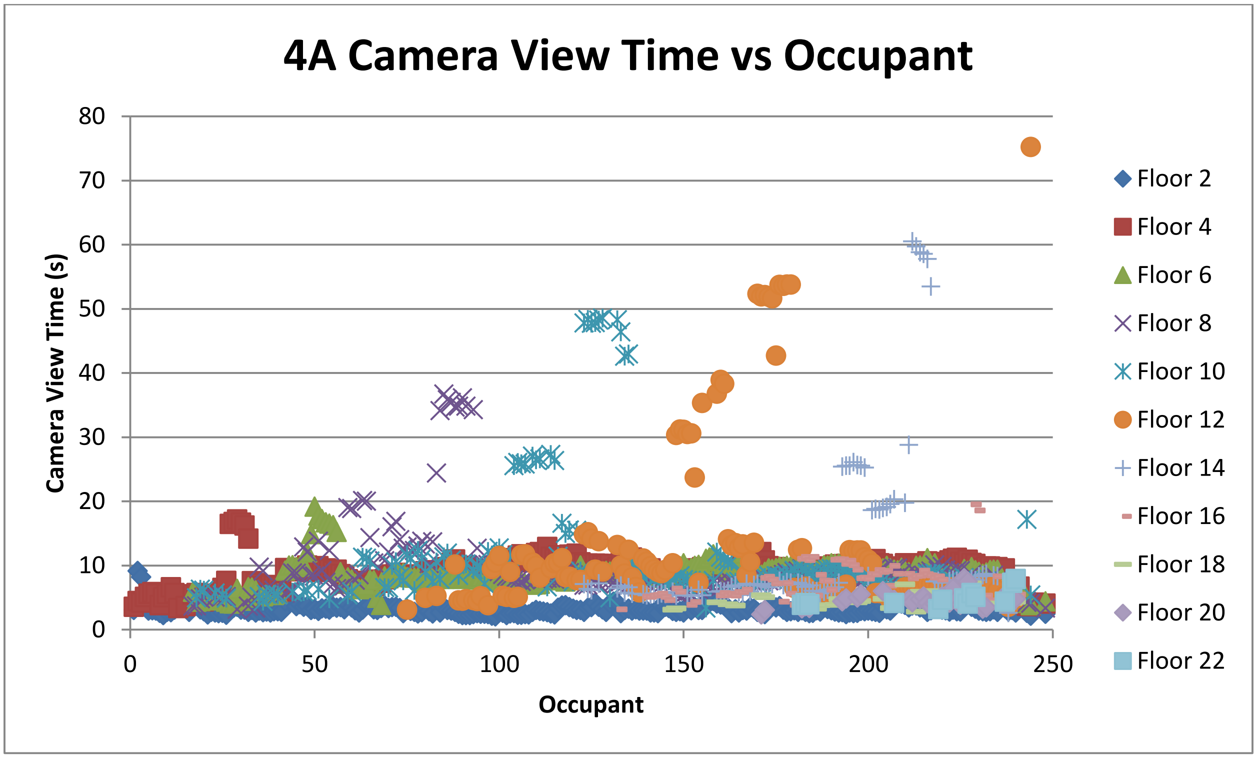
Because this platoon analysis was only conducted on the evacuations of seven stairwells within four different high-rise buildings, more analyses need to be conducted on other egress data of different occupancies to understand if the same results occur. Conducting this study in a variety of occupancies could affect the presence of social groups which would help to understand the relationship, if any exists, between social groups and platoons. Furthermore, different occupants may involve populations with a variety of age and gender distributions which could affect platoon formation.

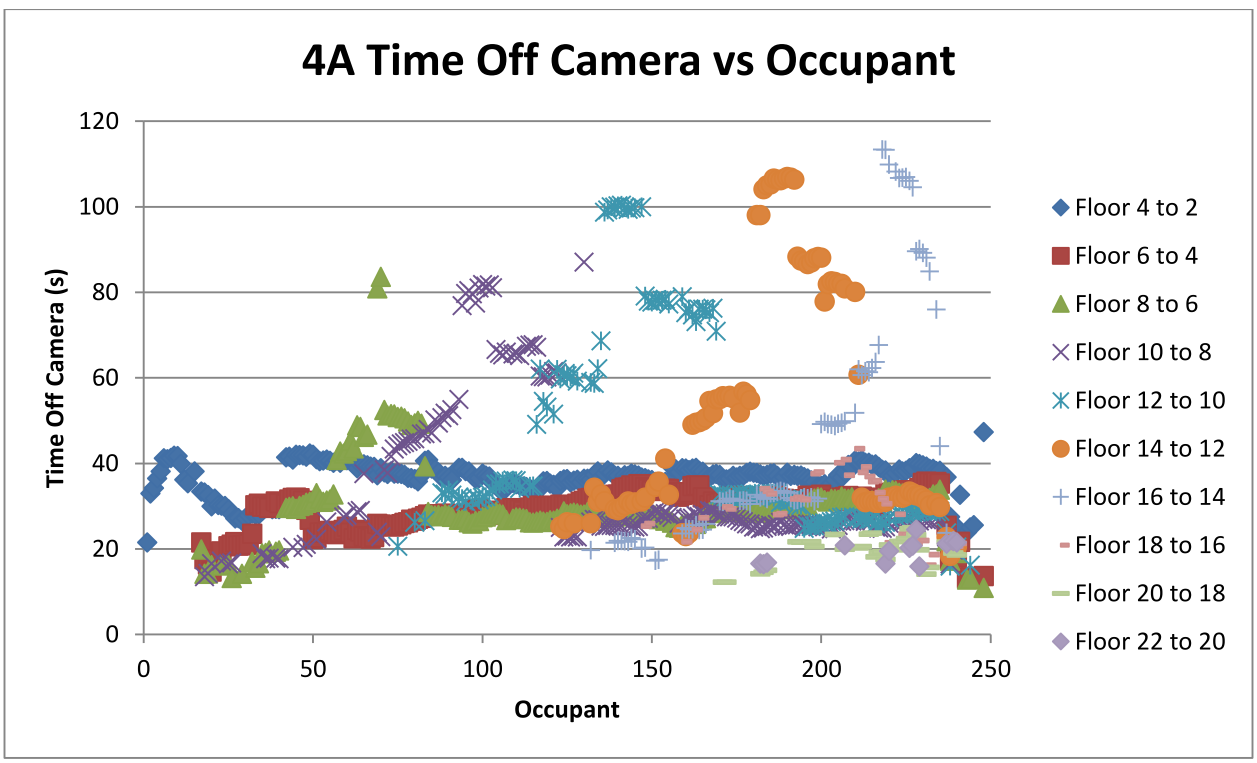
Furthermore, more analyses need to be conducted with other computer egress models to determine if platoons exist within these models. It is assumed that both flow-based models and fine-network models will not accurately simulate platoons; however, a platoon analysis needs to be conducted on these models to see if platoons appear. In analyzing the platoons of agent-based egress models, more quantitative results need to be calculated. These results need to be quantified in the same manner that the empirical platoons were calculated. Also, these results should be compared to the empirical platoon data to determine if platoons frequently remain unchanged during a descent between floors and if platoons are frequently one-person platoons. Understanding if platoons frequently remain unchanged and consist of one person may lead to more accurate model simulations because smaller platoons typically travel faster than larger platoons.

Finally, in comparing SFPE mode to steering mode in Pathfinder, the total egress times for steering mode are less than those in SFPE mode. Because steering mode provides a more realistic representation of platoon behavior during egress, an analysis needs to be conducted to determine if the results in steering mode more accurately represent an evacuation time. Why do the evacuations times take longer when no passing occurs? This question needs to be addressed to understand if the results in steering mode are more accurate than those in SFPE mode.

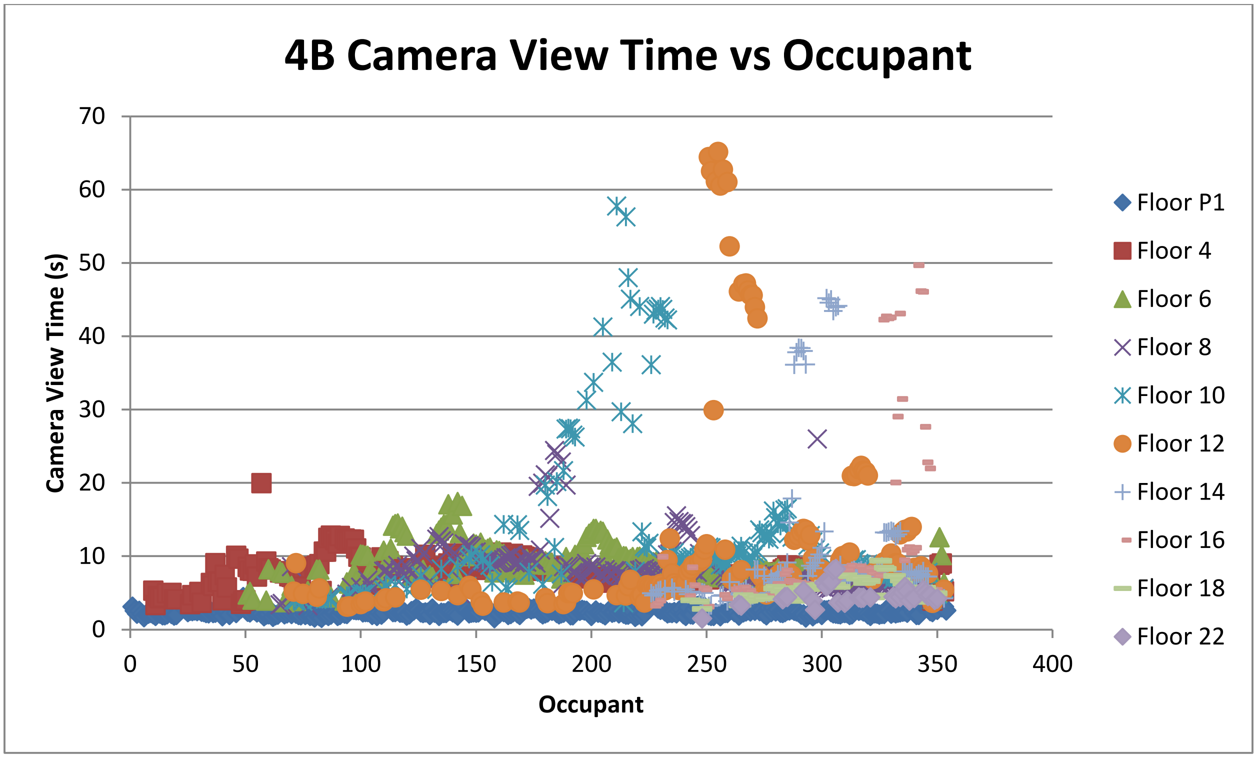
Appendix A: Camera and Off Camera Times

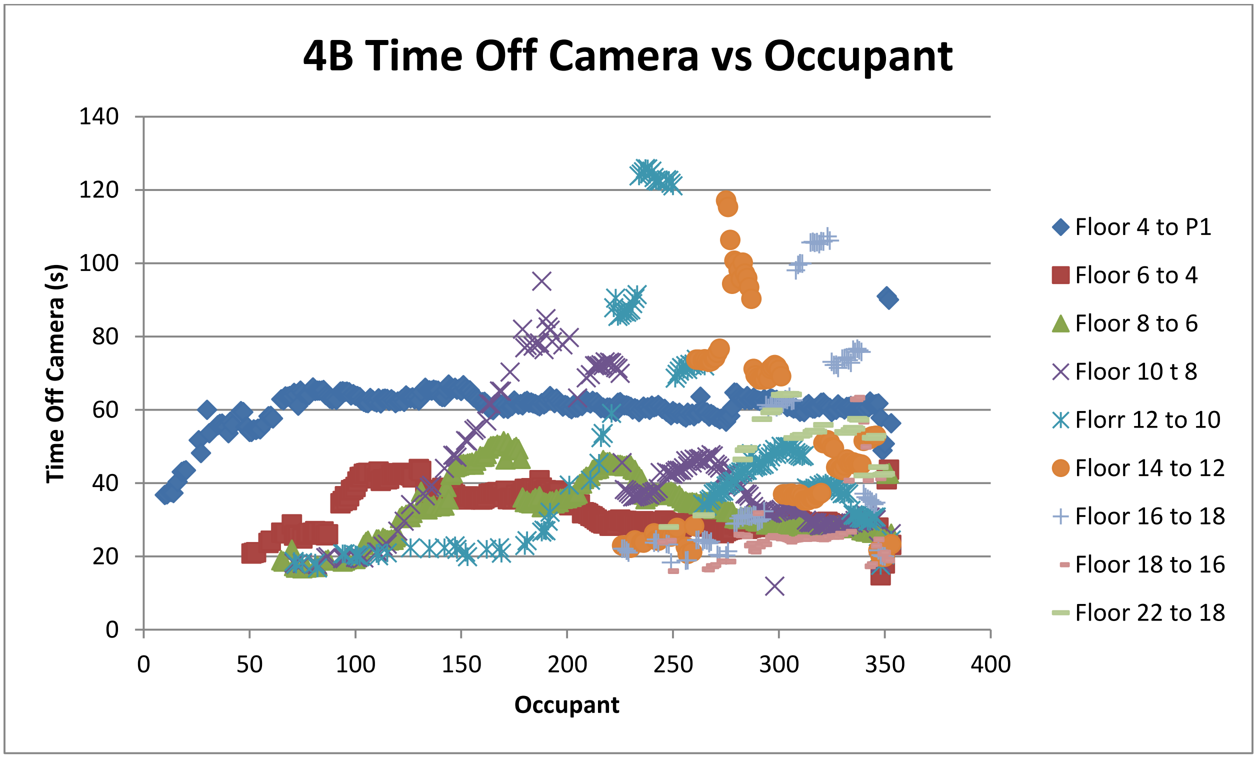
Stairwell 4A



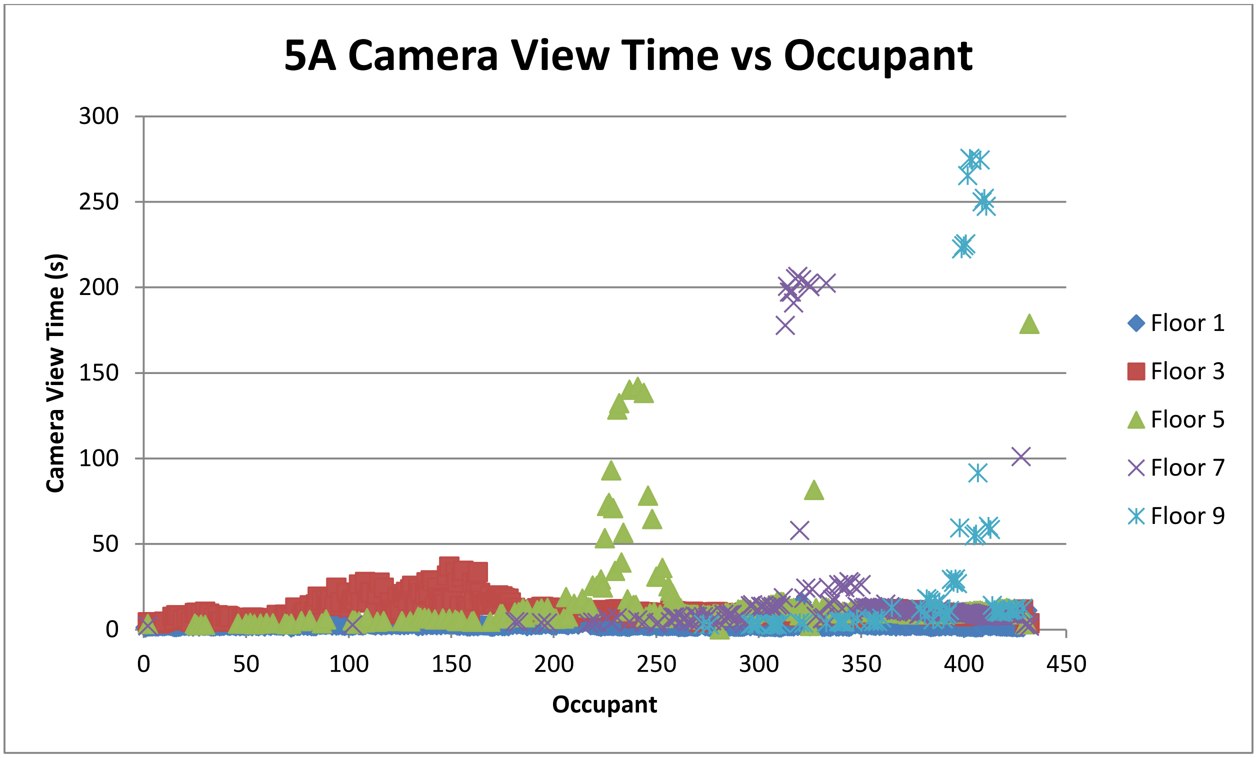


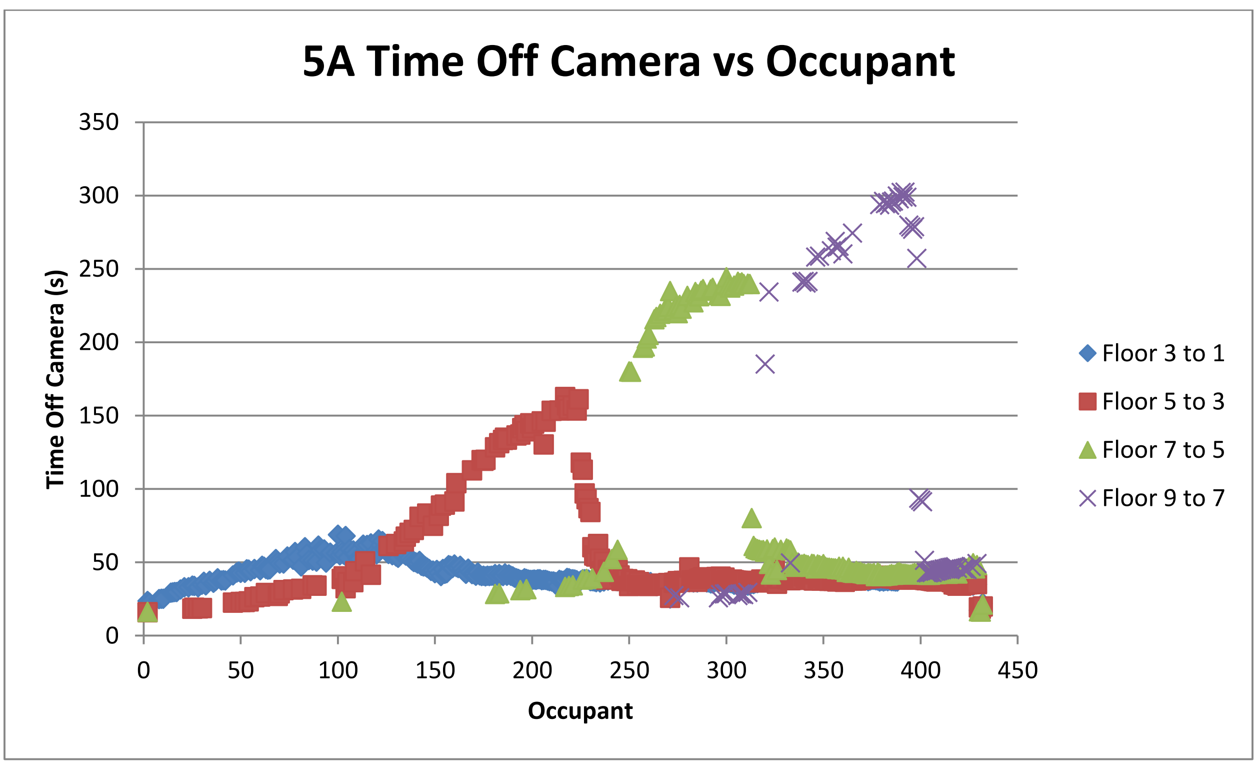
Stairwell 4B



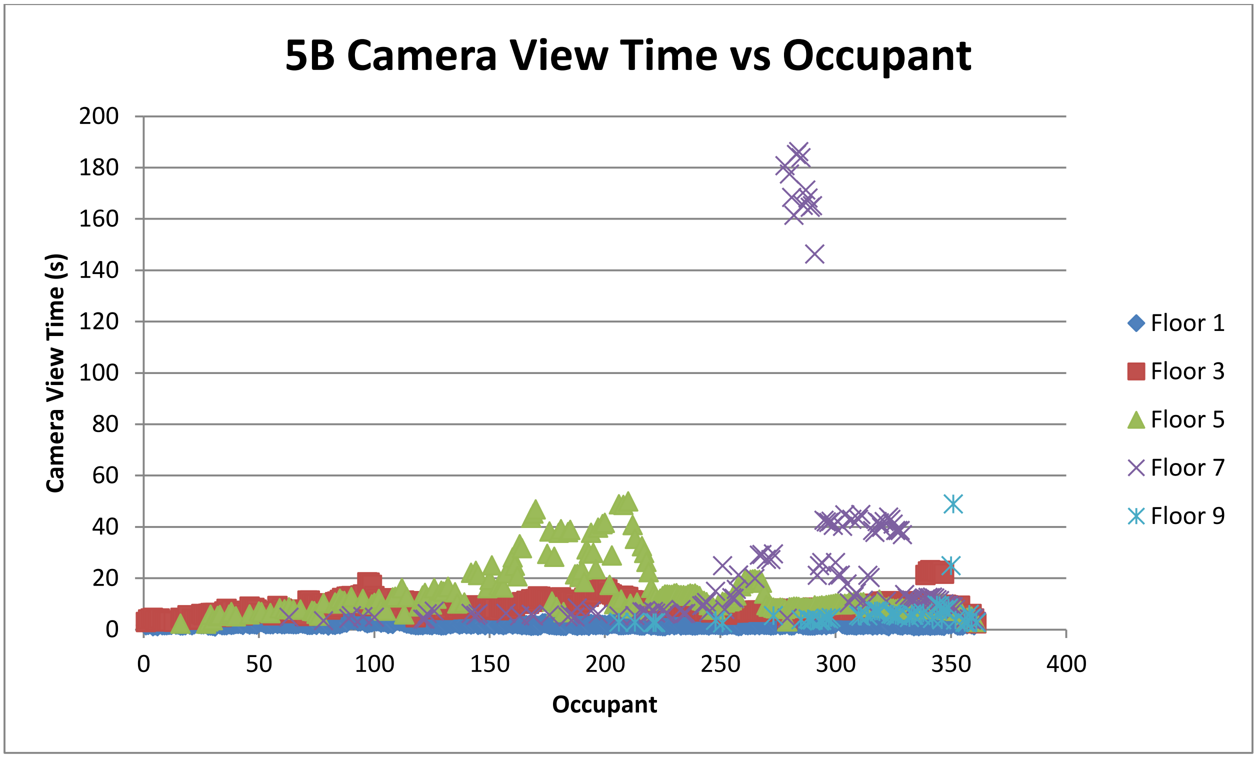


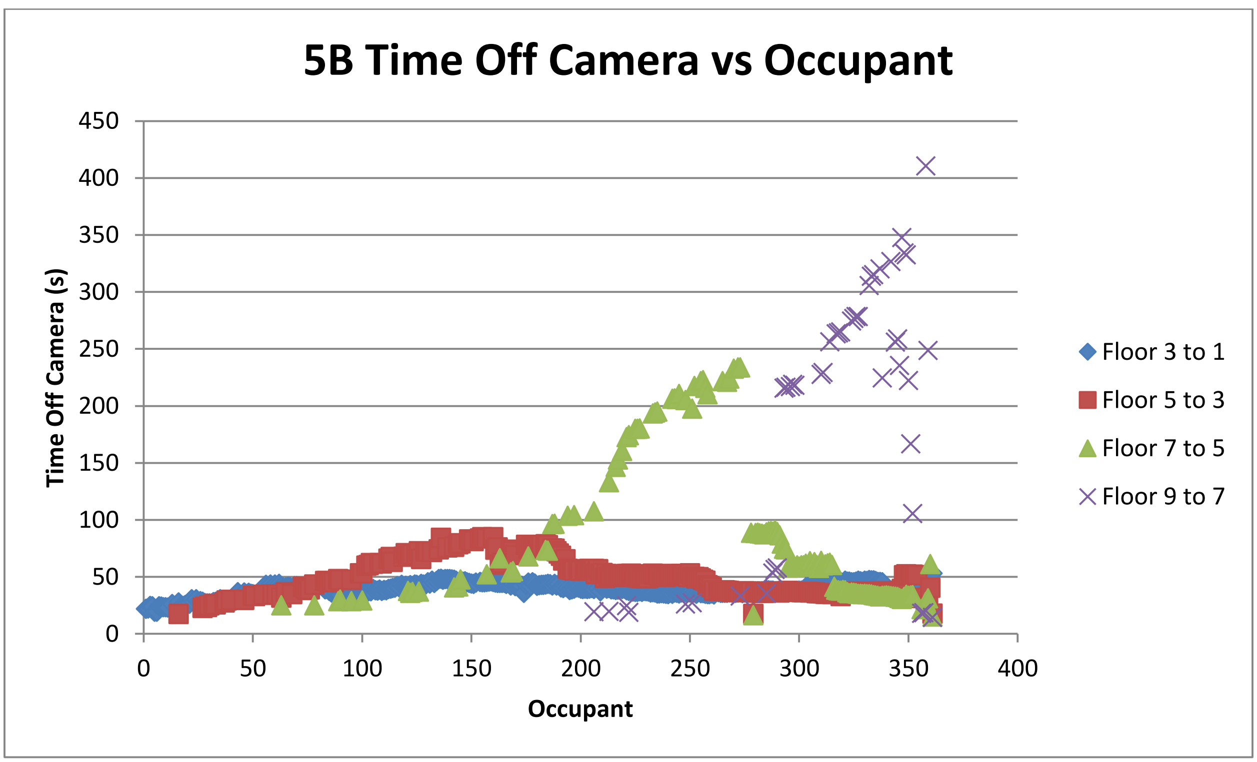
Stairwell 5A



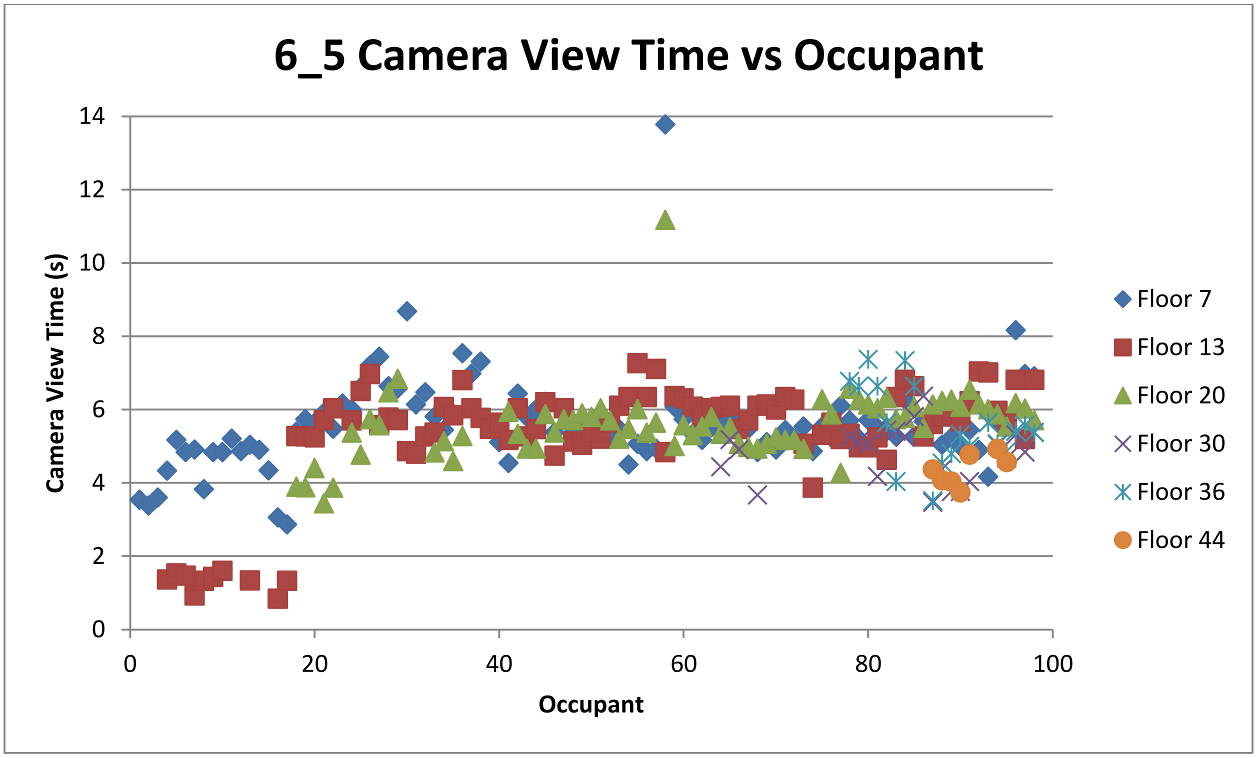


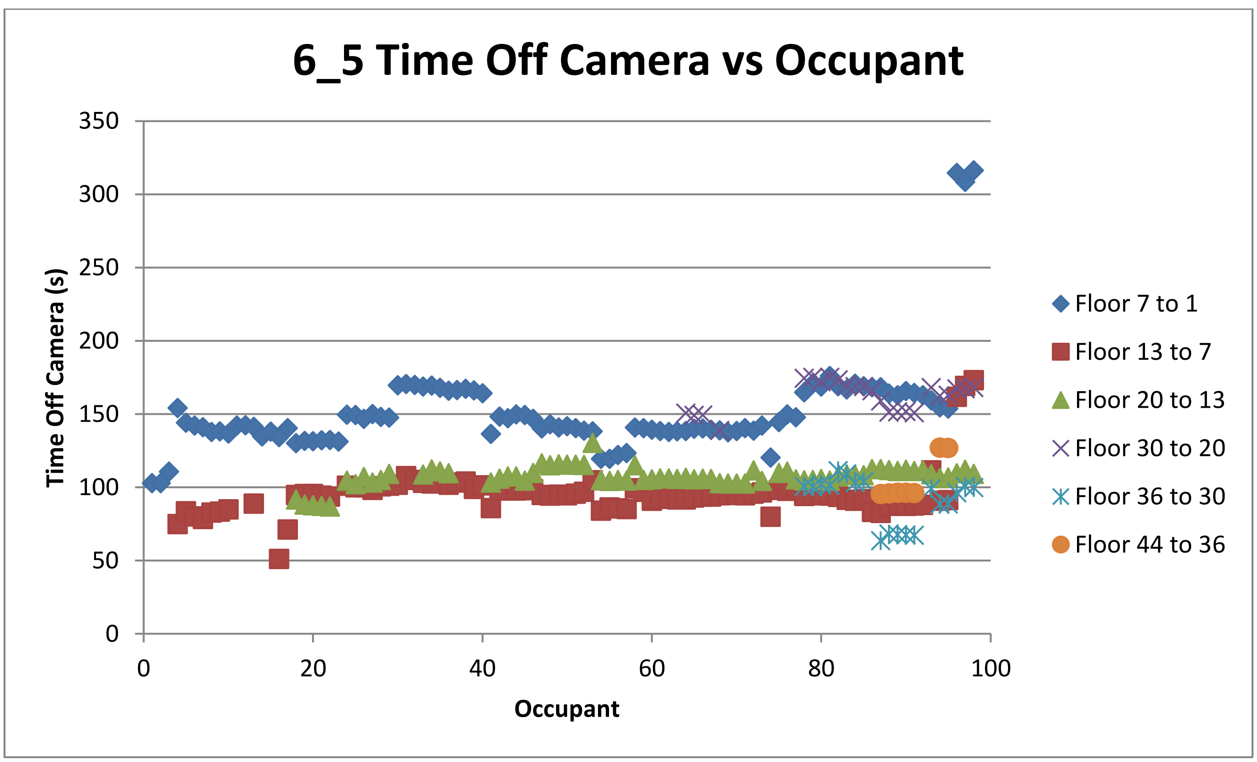
Stairwell 5B



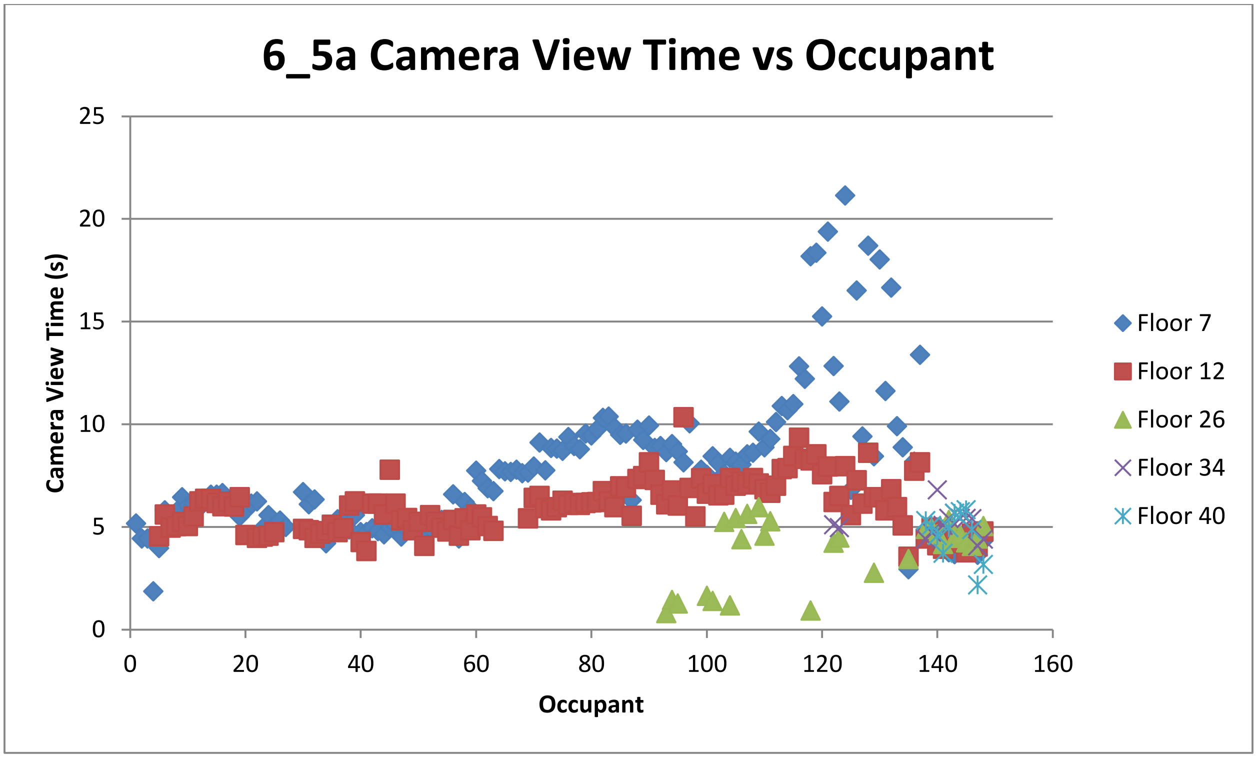


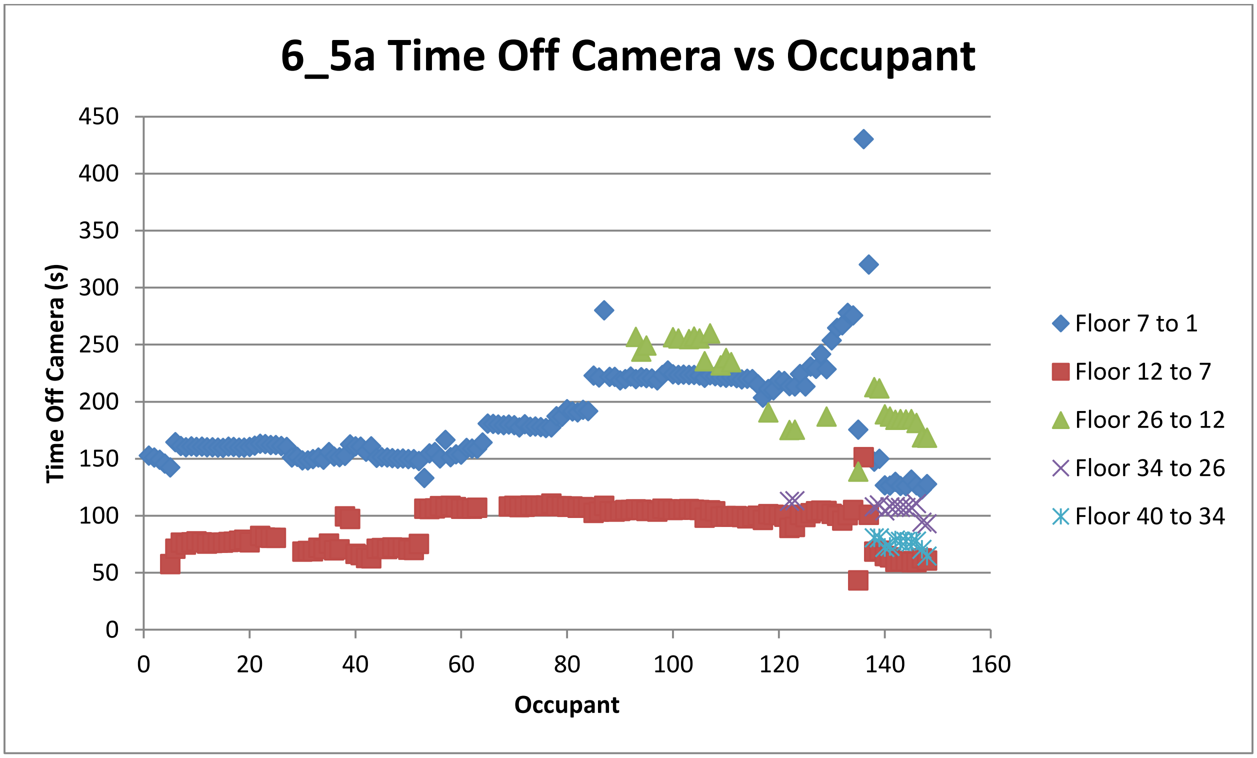
Stairwell 6_5



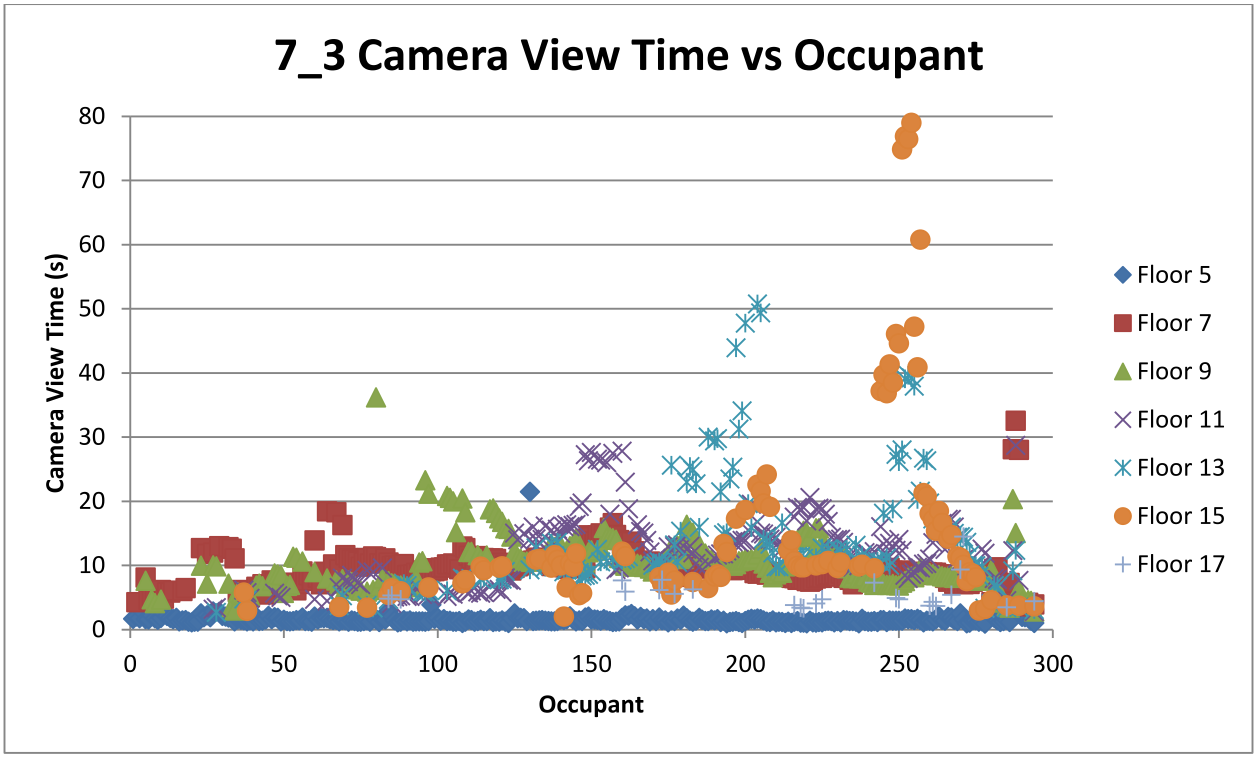


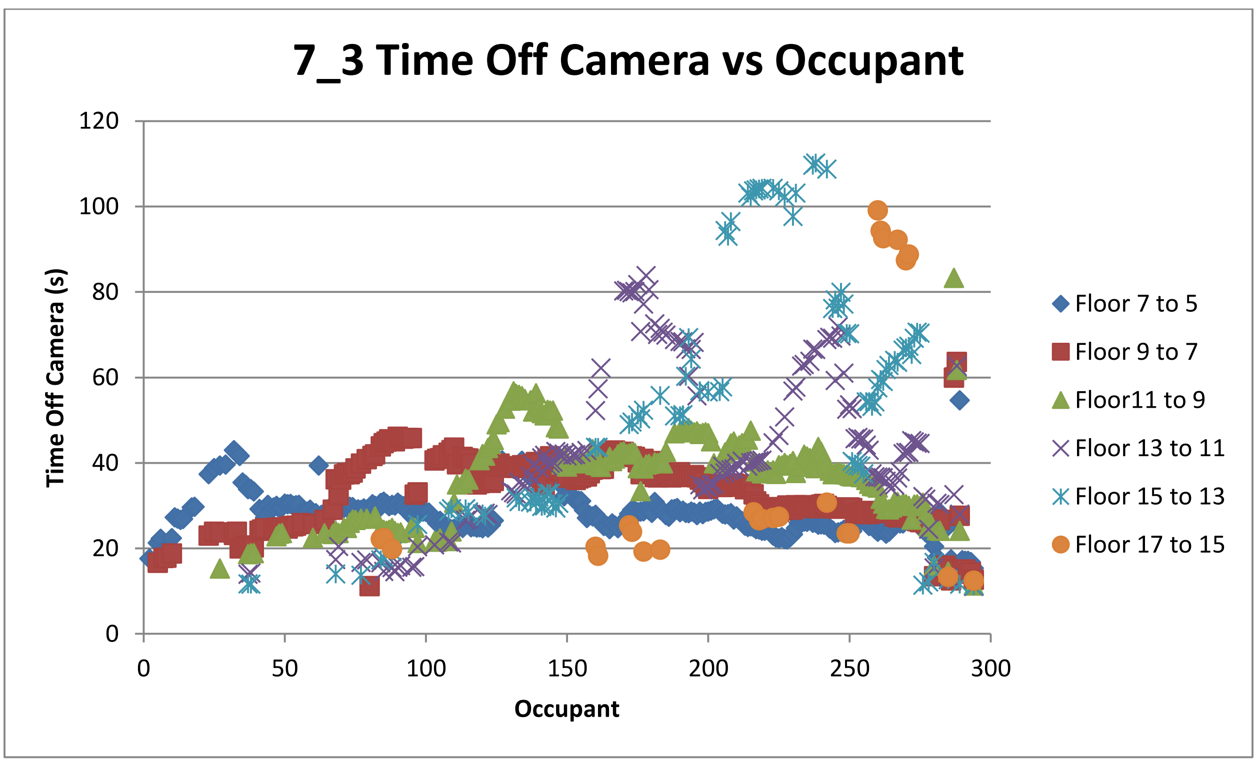
Stairwell 6_5A





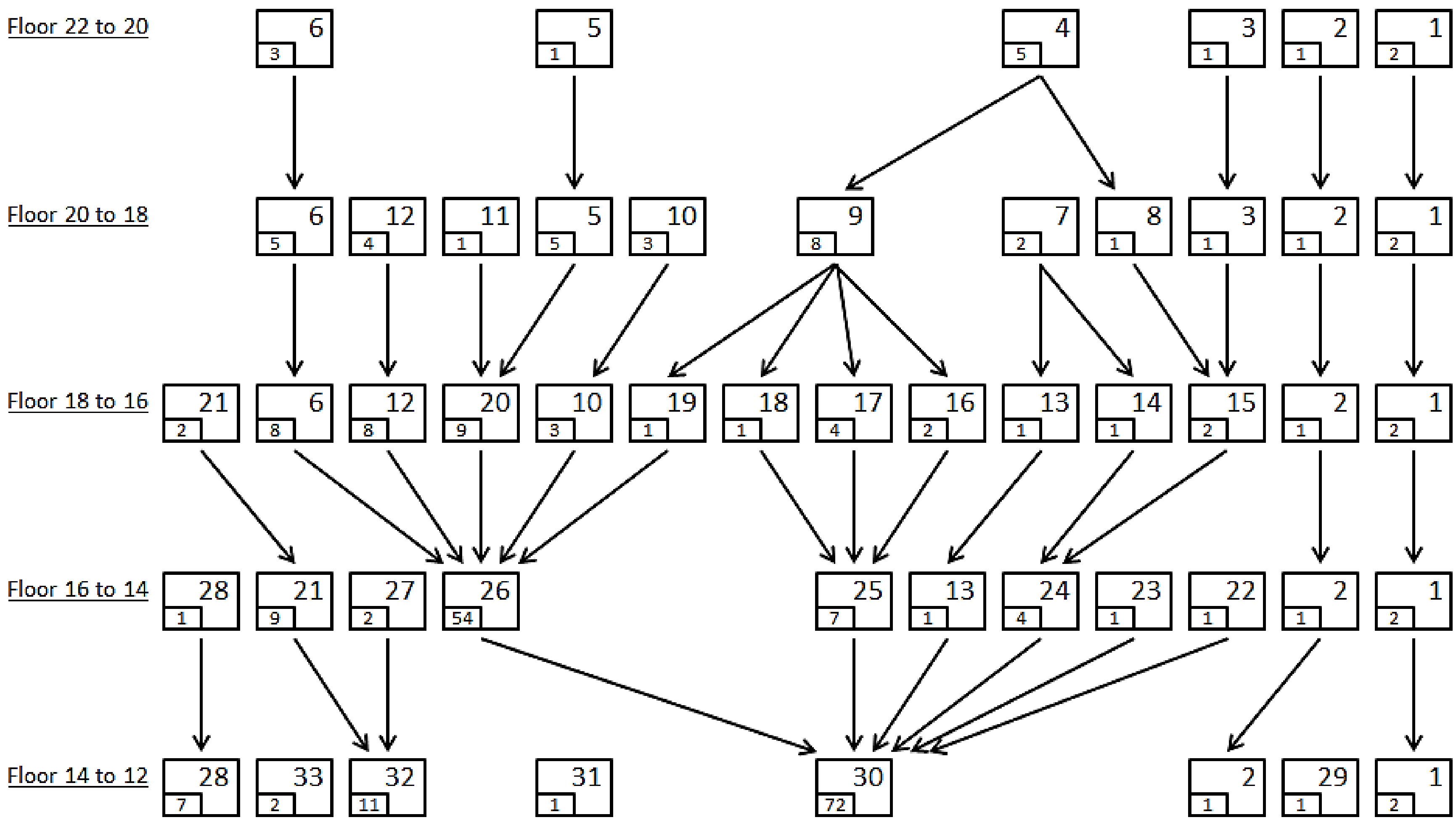
Stairwell 7_3

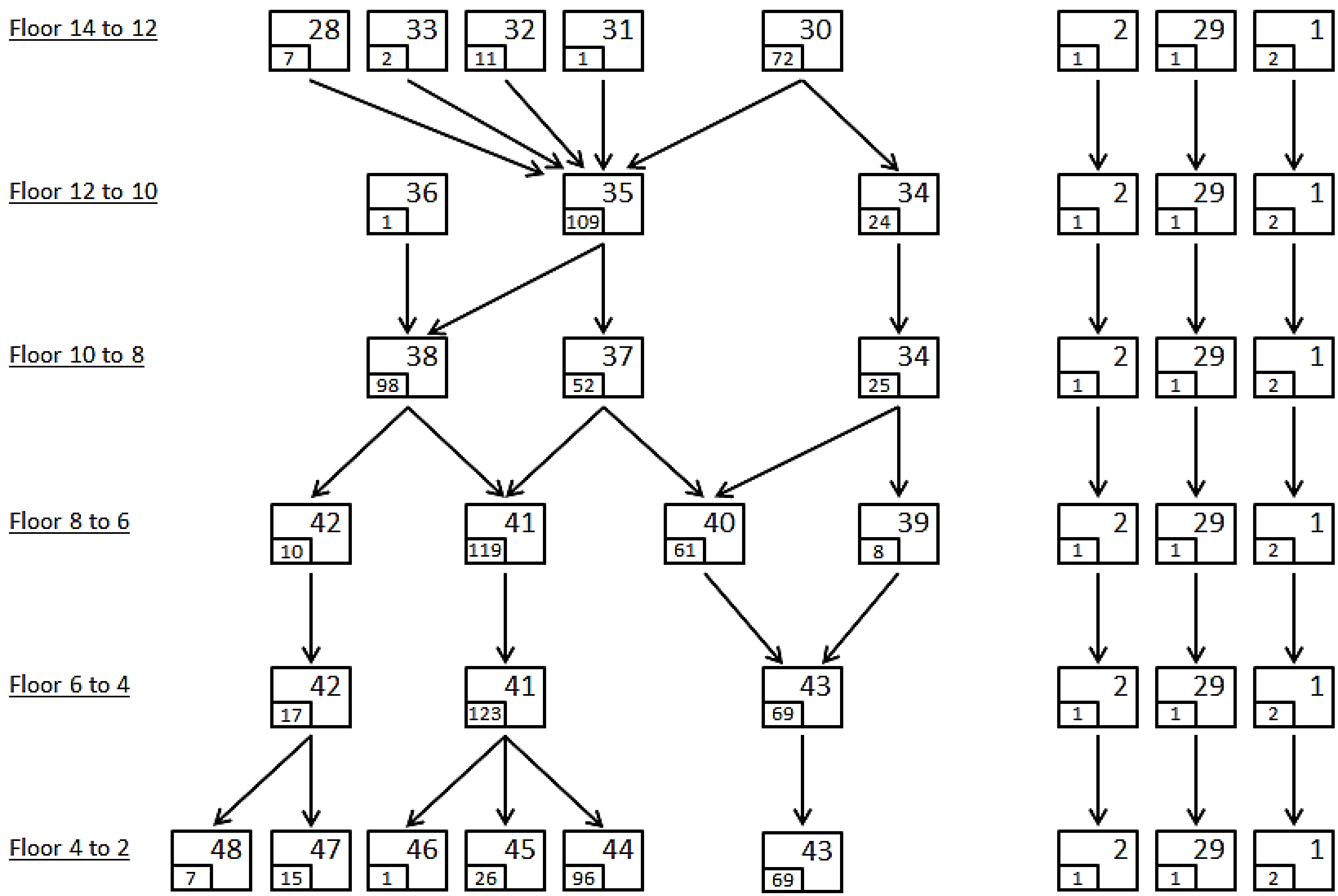




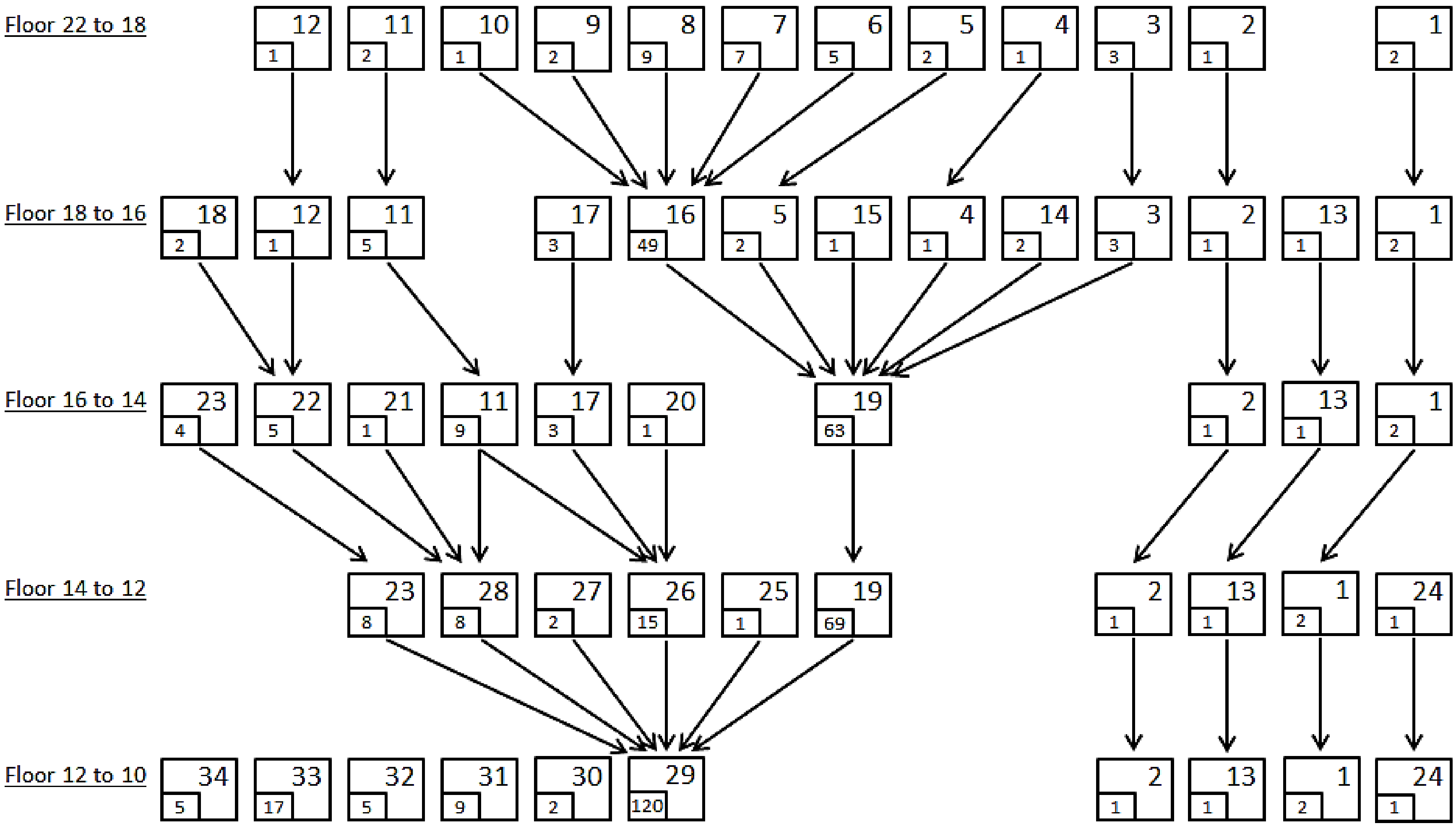
Appendix B: Platoon Flowcharts

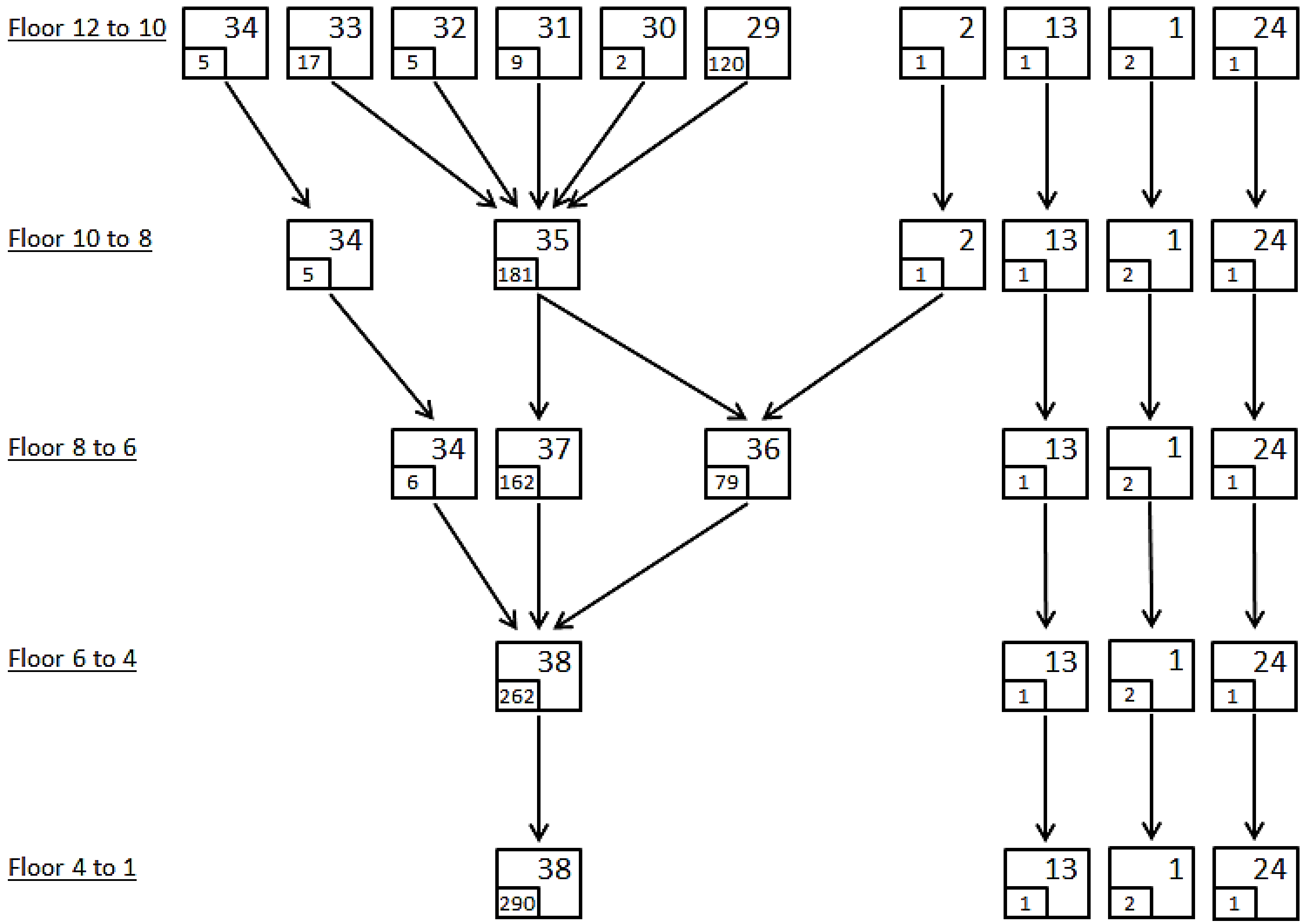
Stairwell 4A




Floor 14 to 12
Floor 12 to 10
Floor 10 to 8
Floor 8 to 6
Floor 6 to 4
Floor 4 to 2

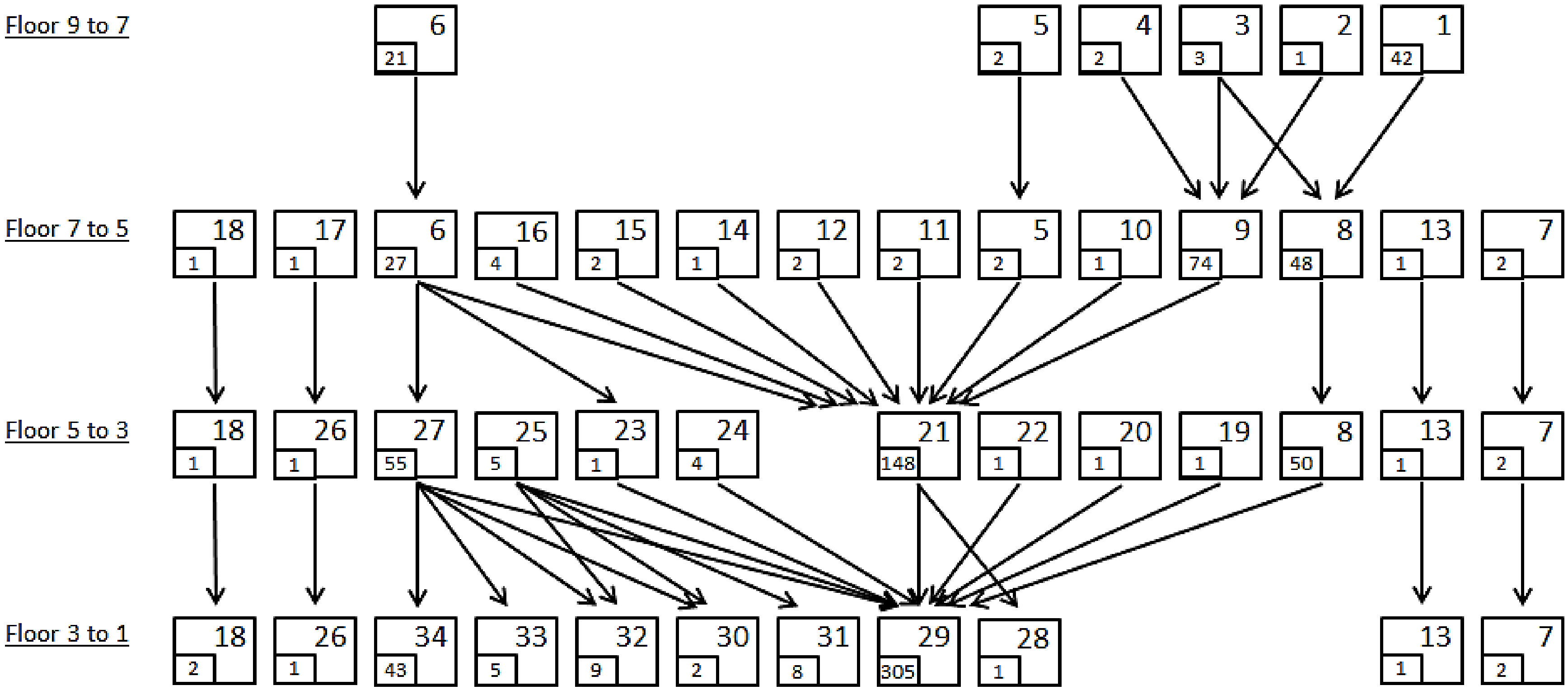
Stairwell 4B



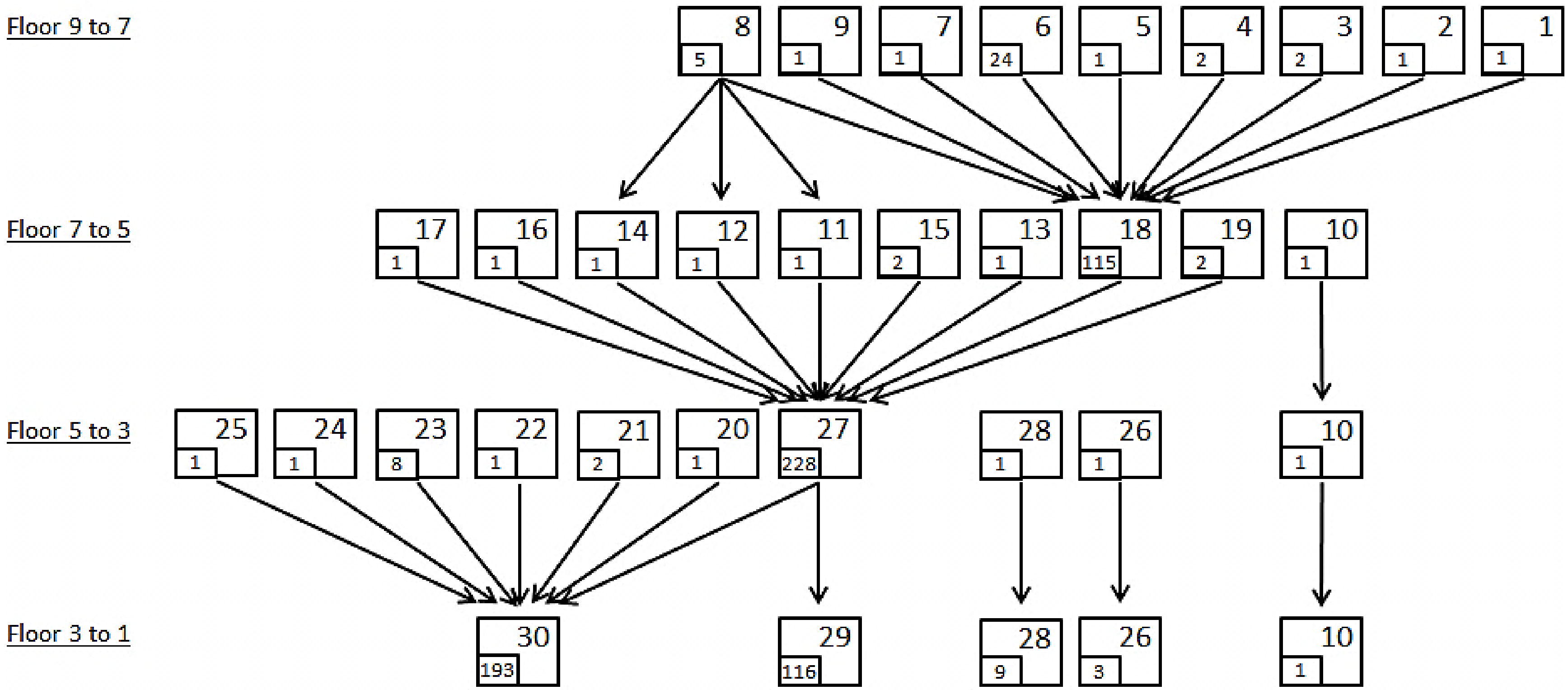


Floor 12 to 10
34
5
33
17
32
5
31
9
30
2
29
120
2
1
13
1
1
2
24
1
Floor 10 to 8
34
5
35
181
2
1
13
1
1
2
24
1
Floor 8 to 6
34
6
37
162
36
79
13
1
1
2
24
1
Floor 6 to 4
38
262
13
1
1
2
24
1
Floor 4 to 1
38
290
13
1
1
2
24
1

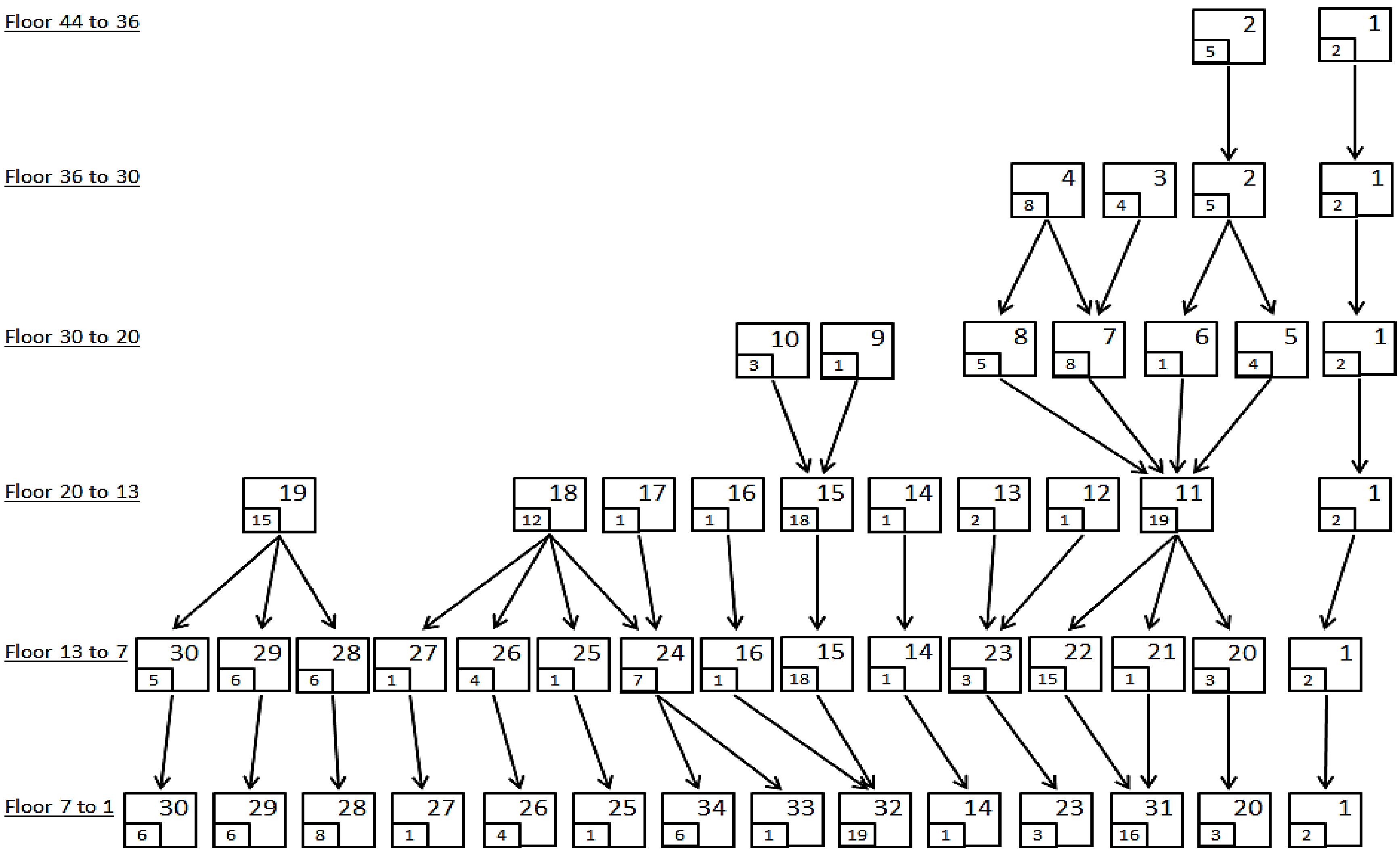
Stairwell 5A



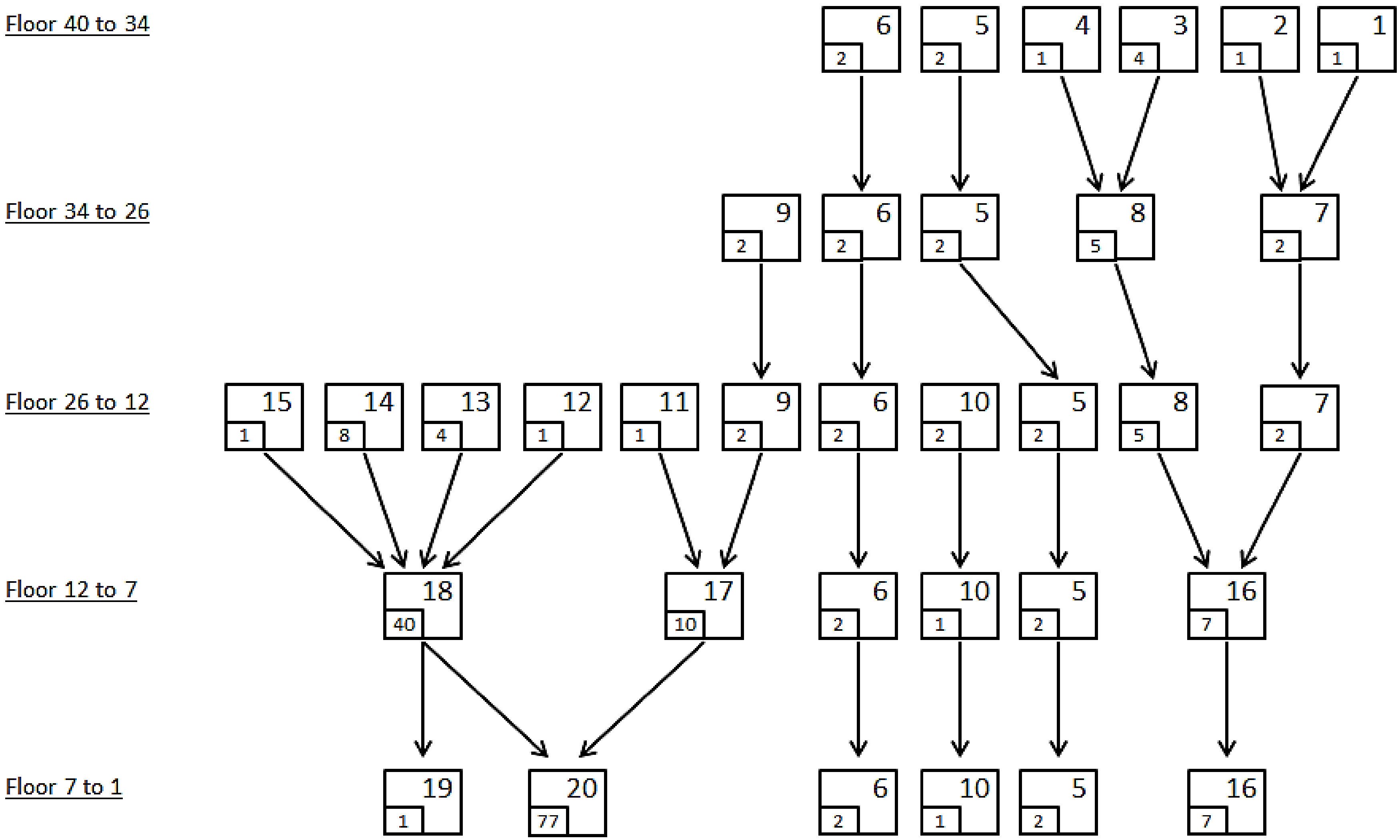
Stairwell 5B



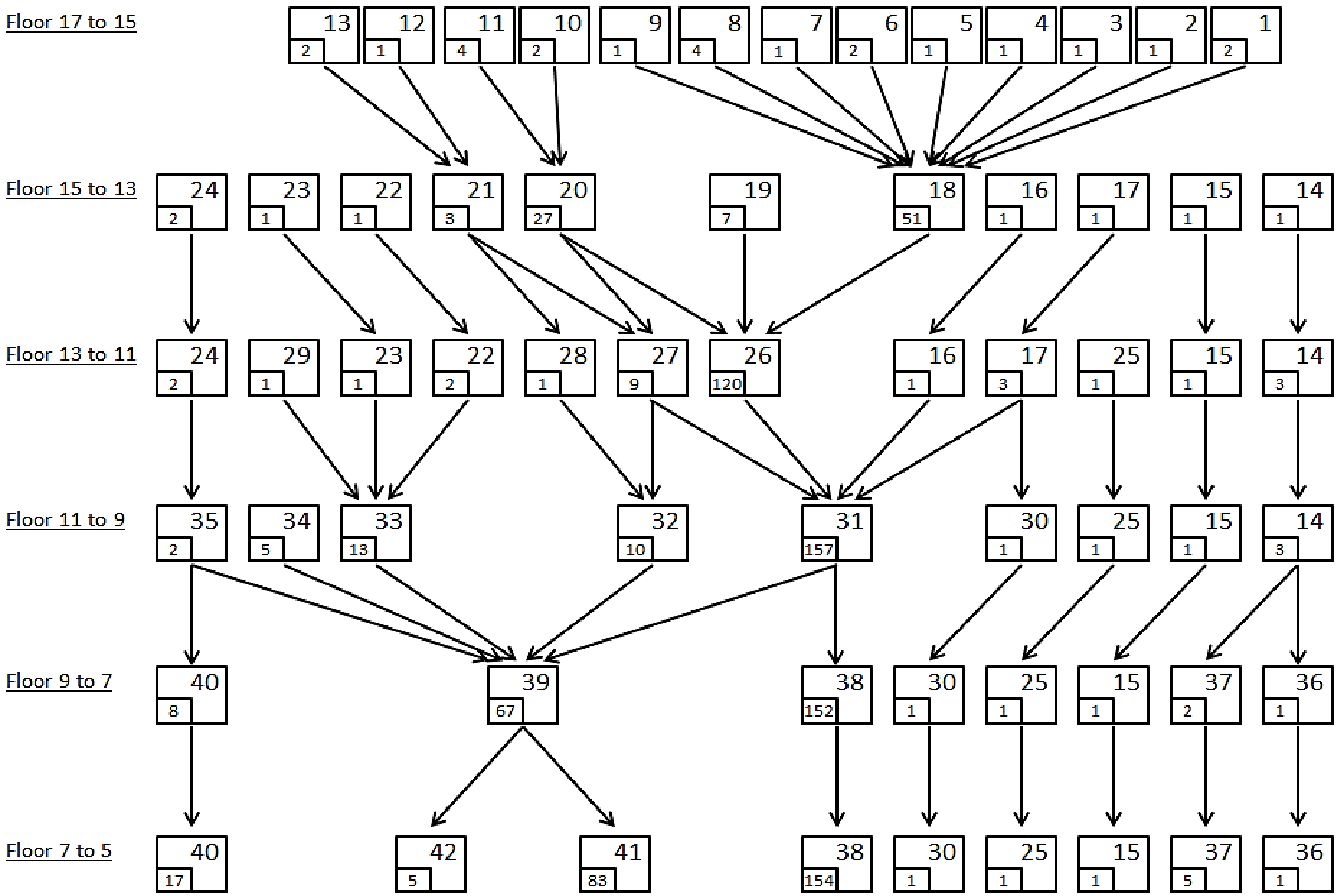
Stairwell 6_5



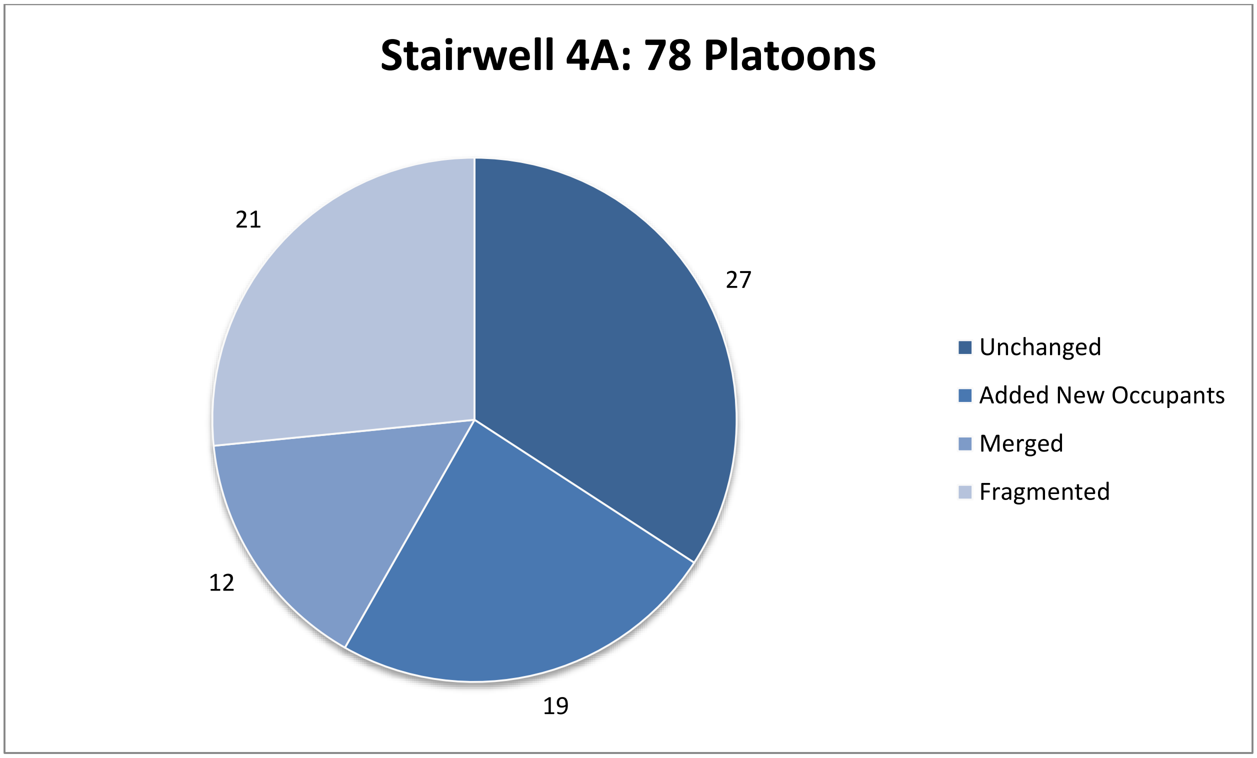
Stairwell 6_5A

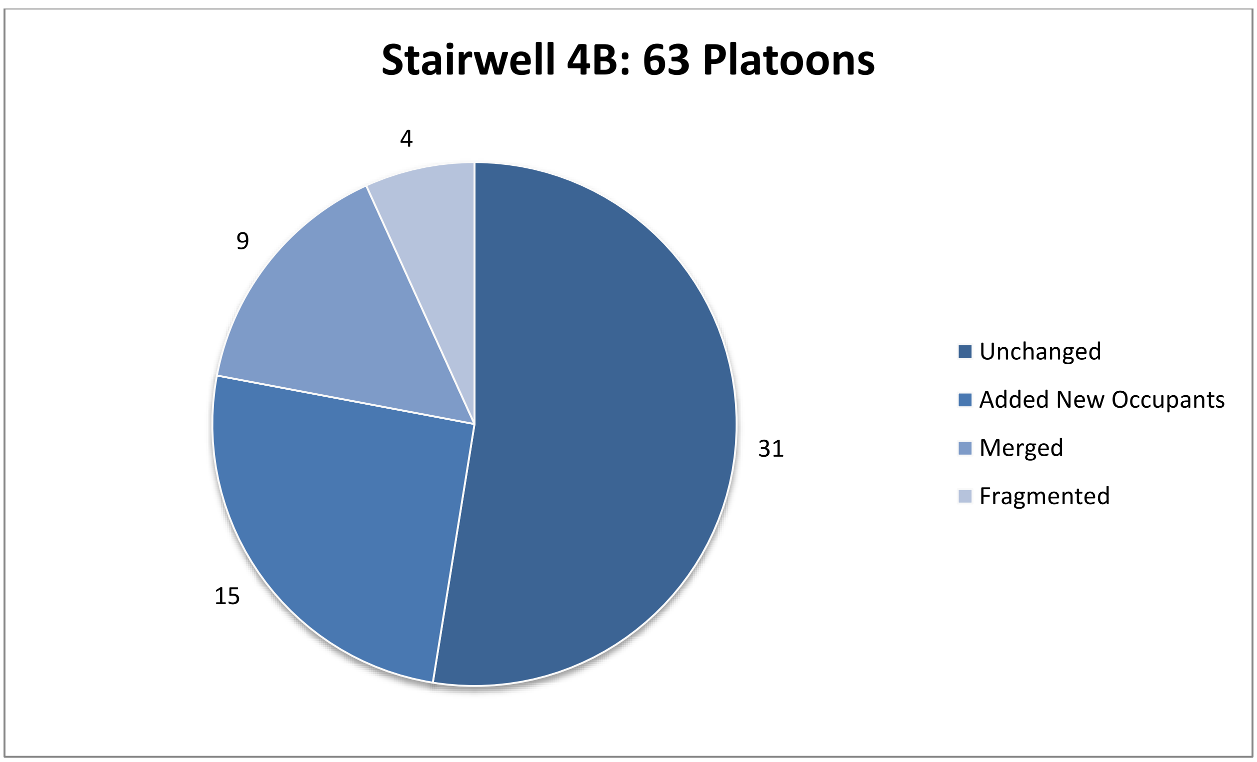


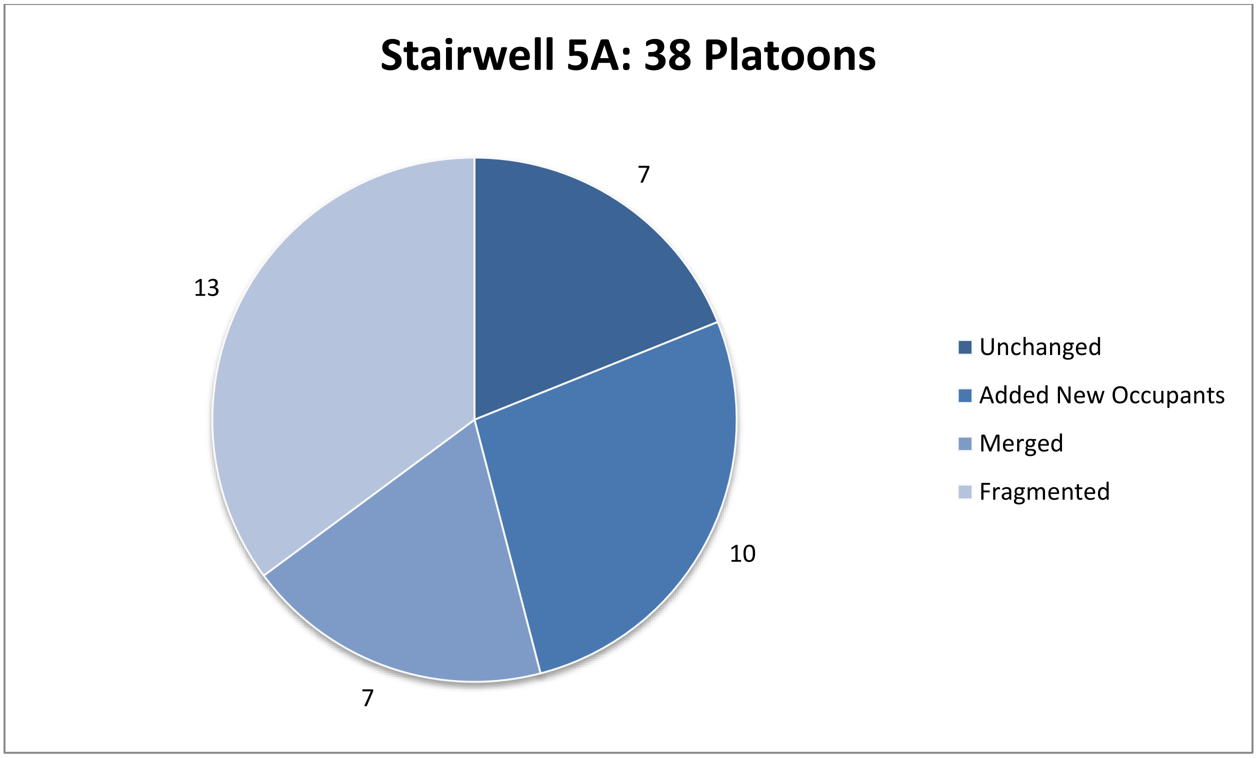
Stairwell 7_3

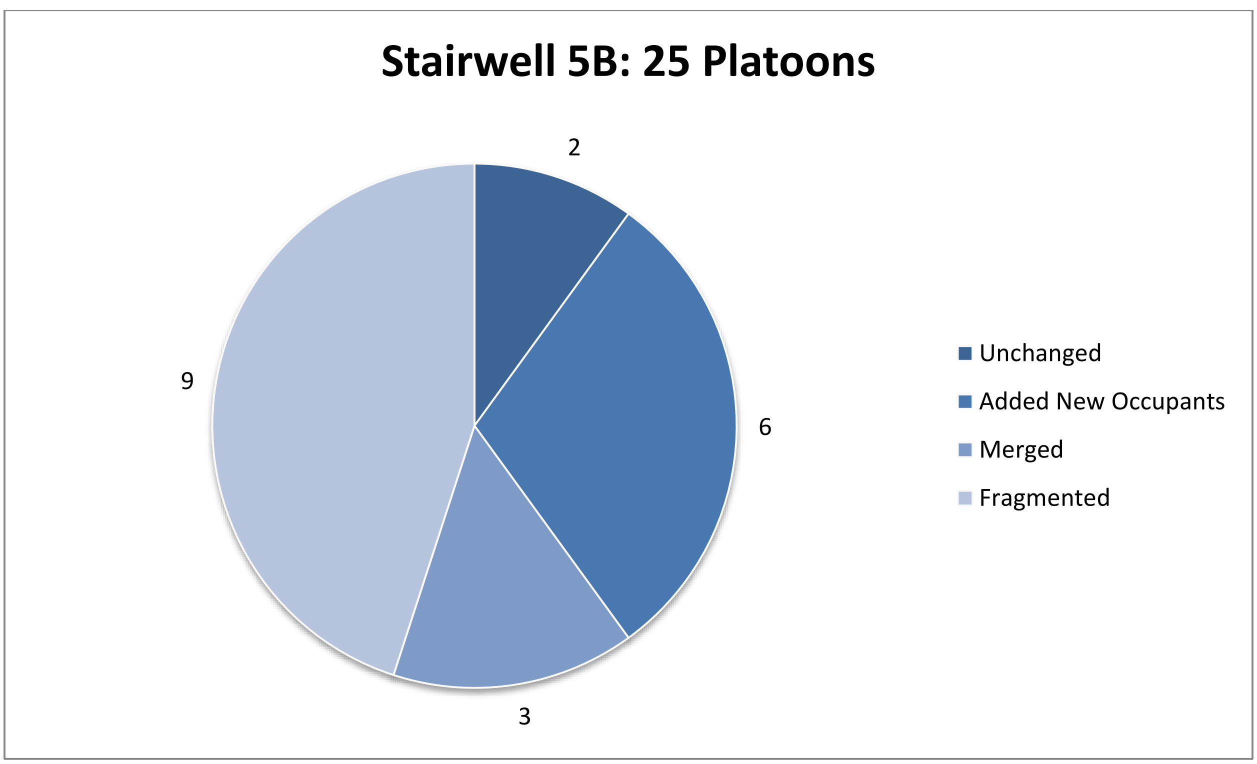


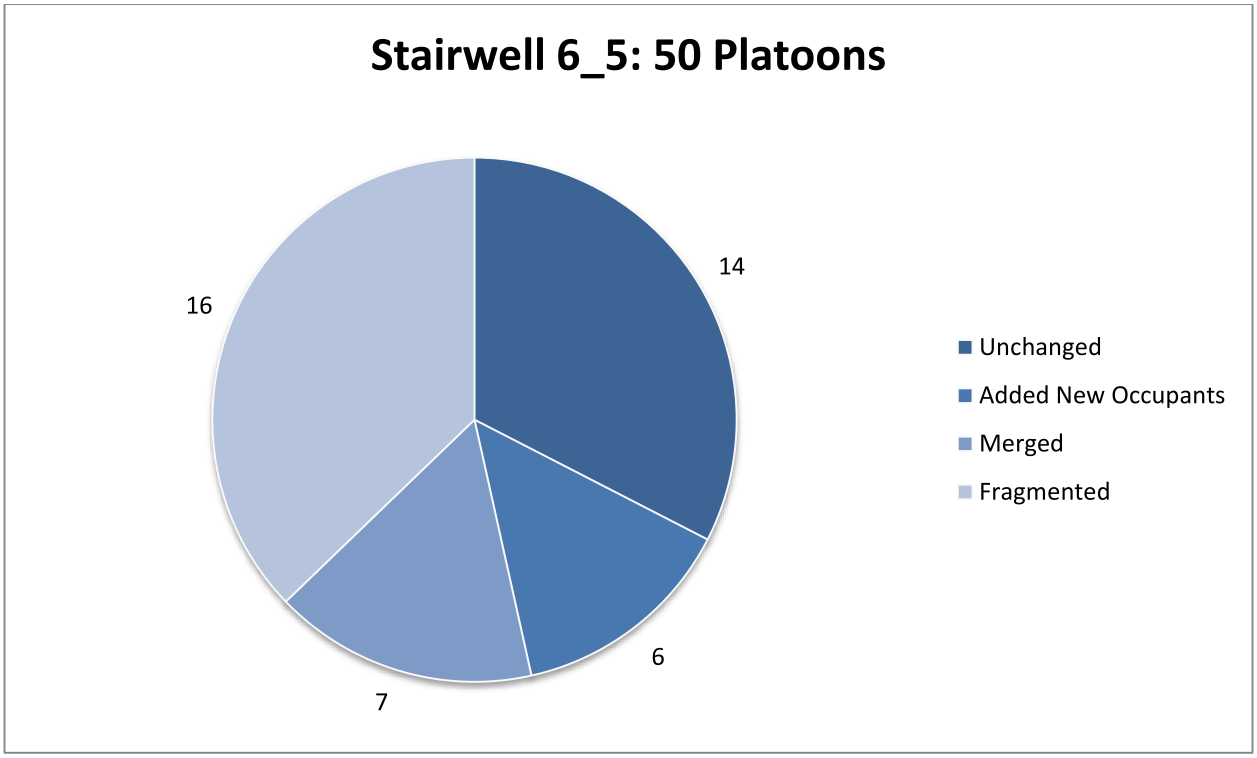
Appendix C: Platoon Variation Pie Charts

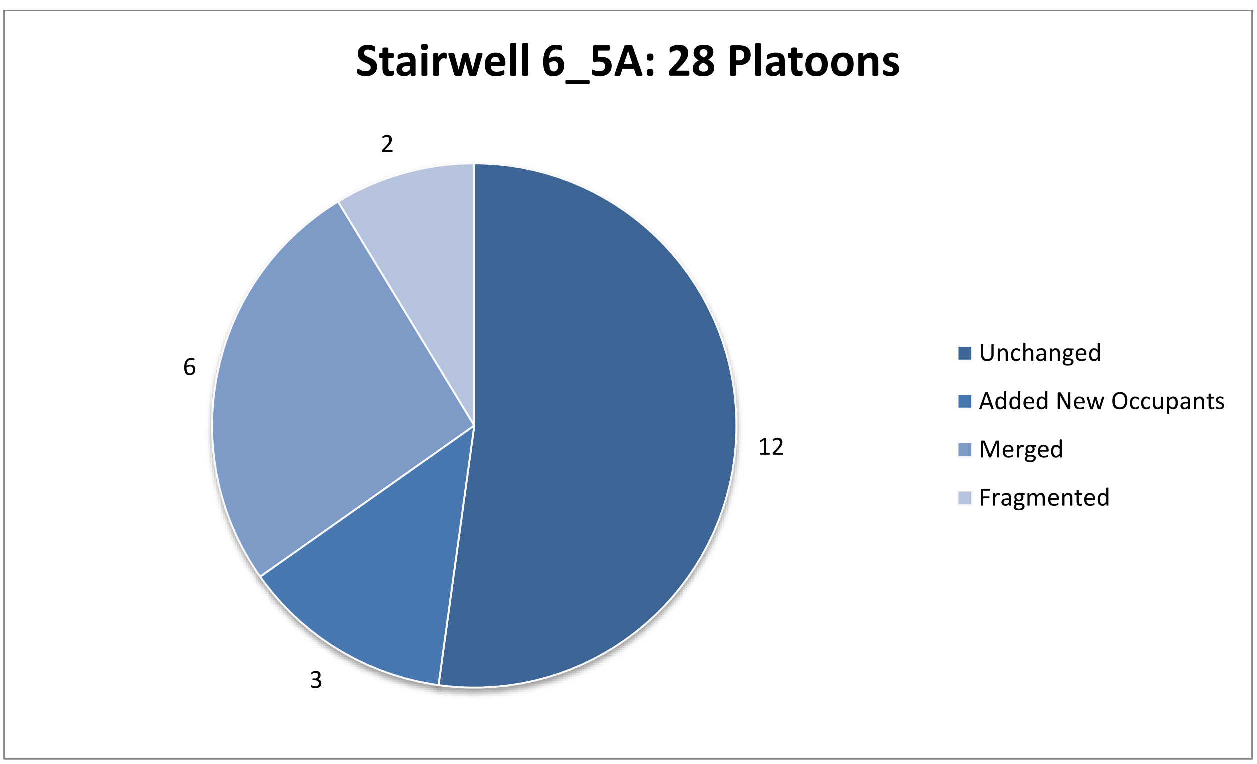


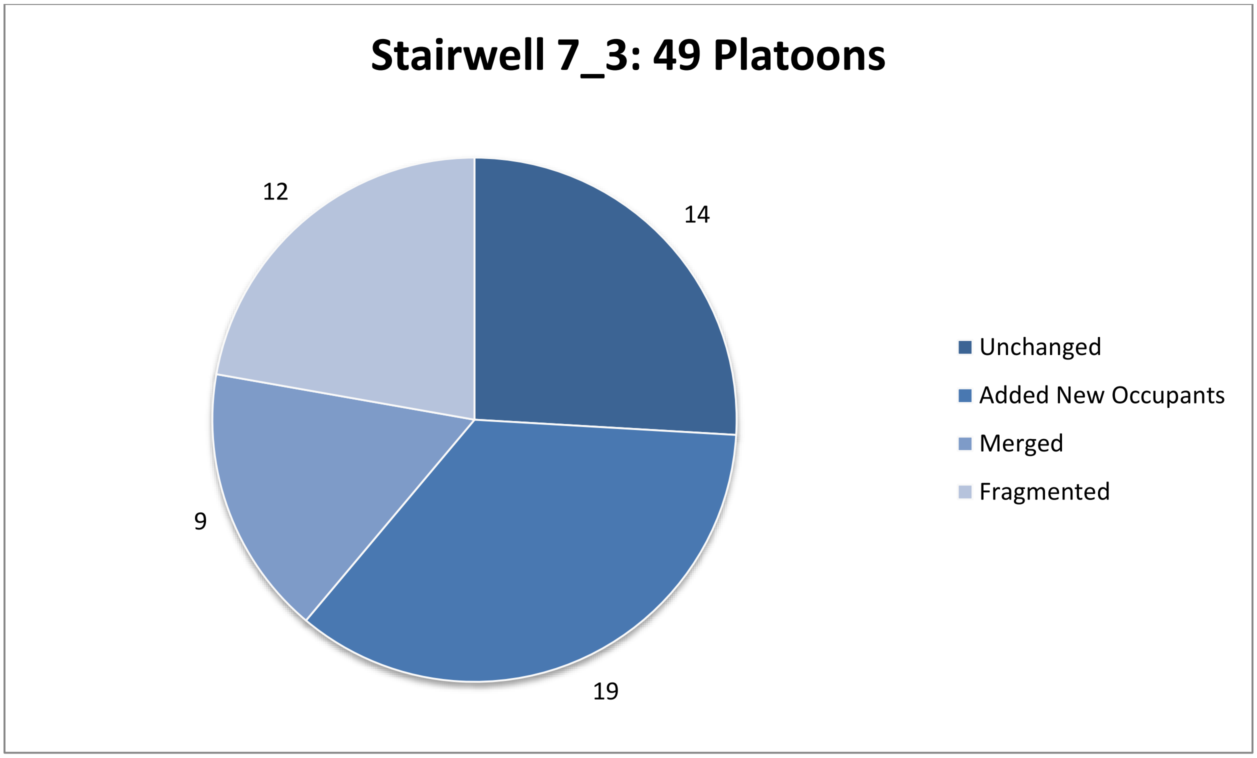


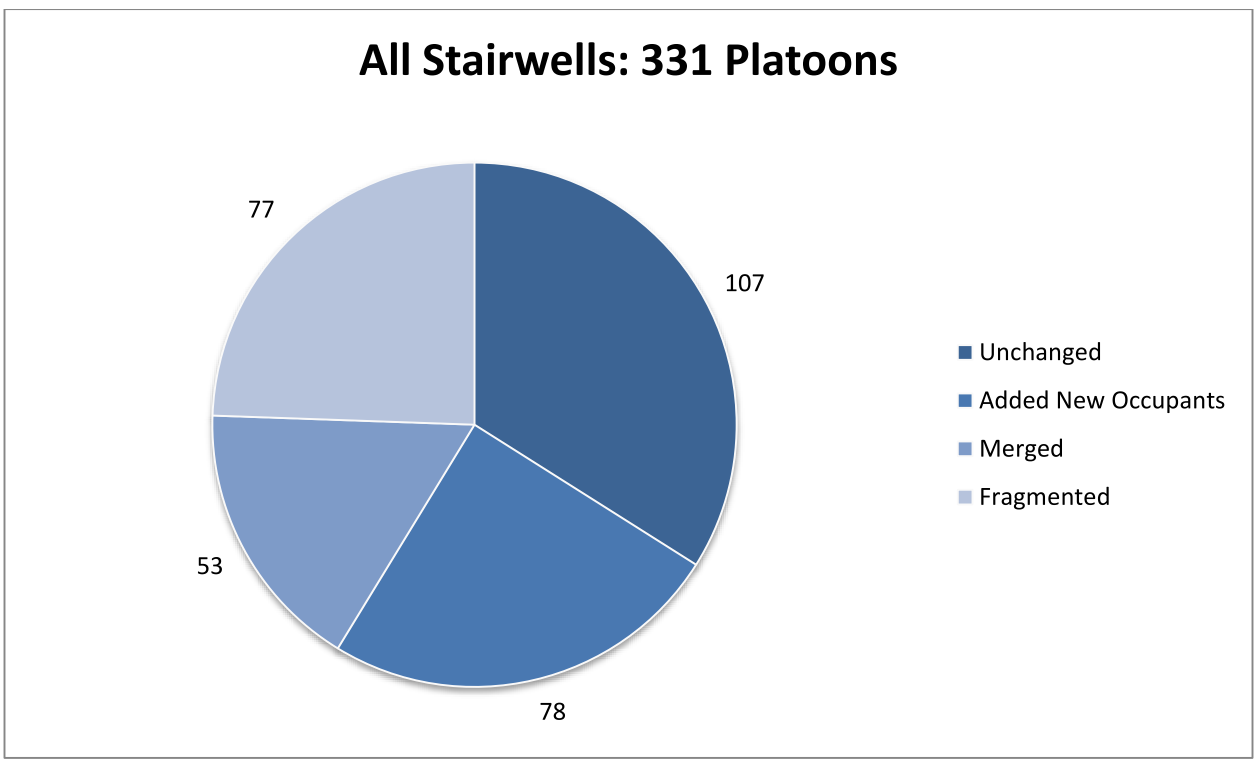

Stairwell 5A: 38 Platoons
7
10
7
13
Unchanged
Added New Occupants
Merged
Fragmented


Stairwell 5B: 25 Platoons
2
6
3
9
Unchanged
Added New Occupants
Merged
Fragmented

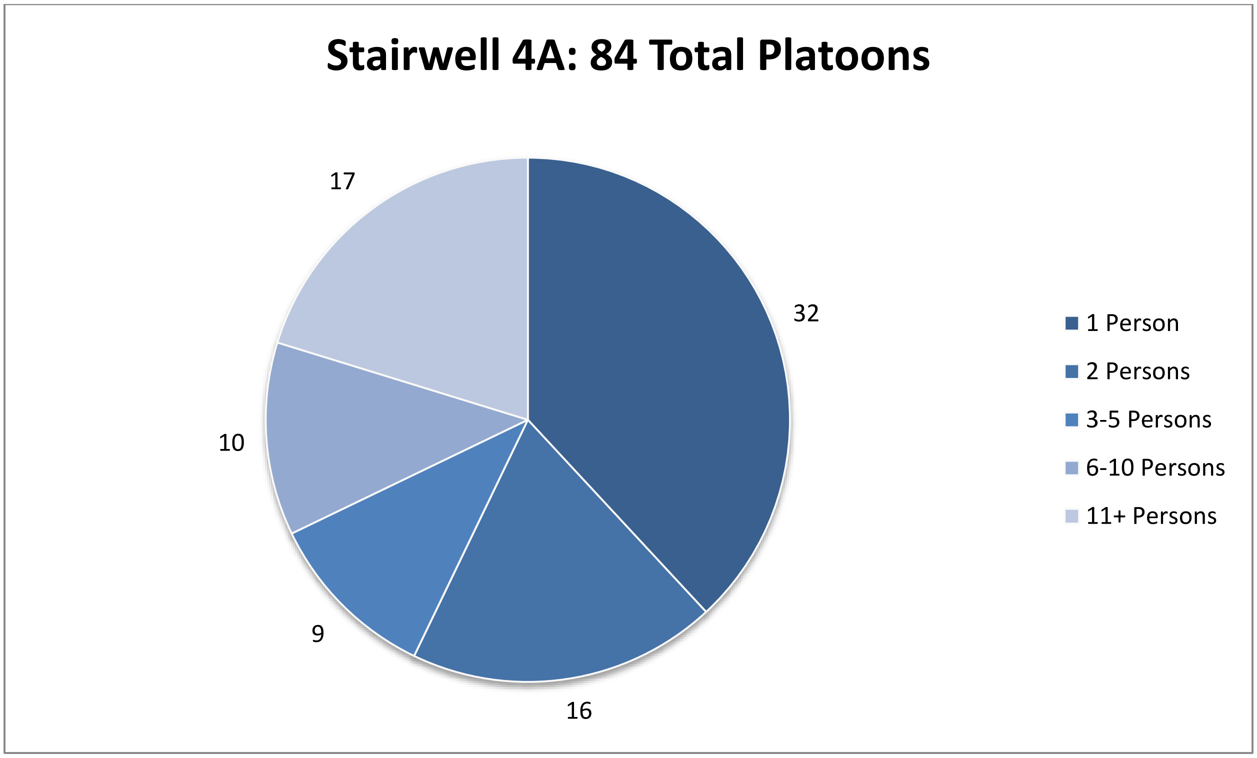

Stairwell 6_5: 50 Platoons
14
6
7
16
Unchanged
Added New Occupants
Merged
Fragmented

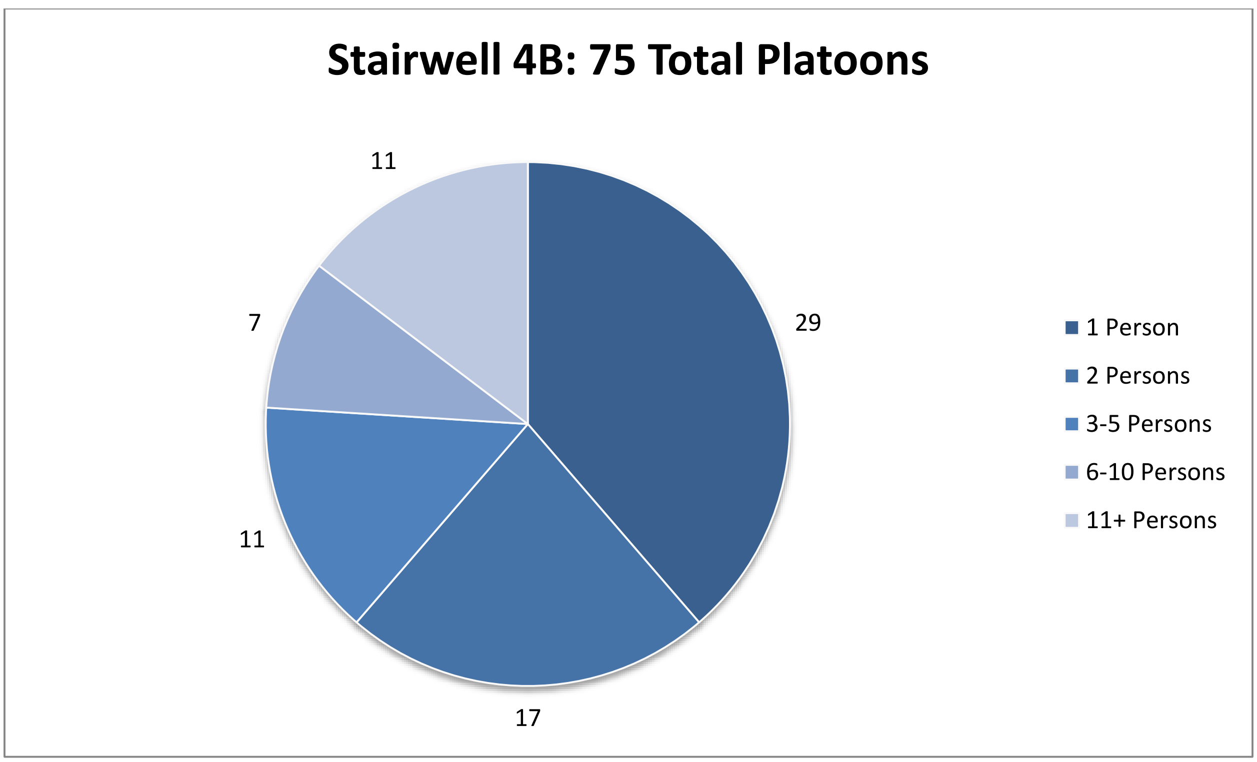

Stairwell 6_5A: 28 Platoons
2
12
3
6
Unchanged
Added New Occupants
Merged
Fragmented

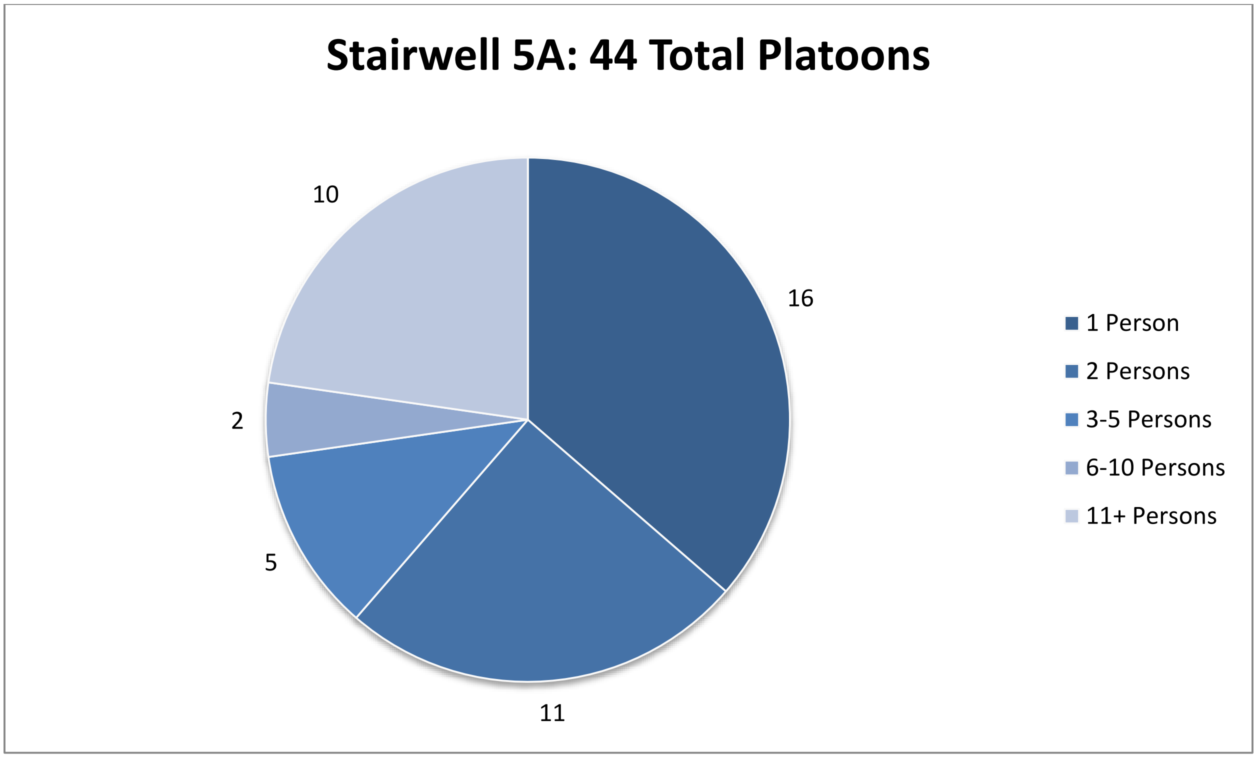

Stairwell 7_3: 49 Platoons
12
14
9
19
Unchanged
Added New Occupants
Merged
Fragmented

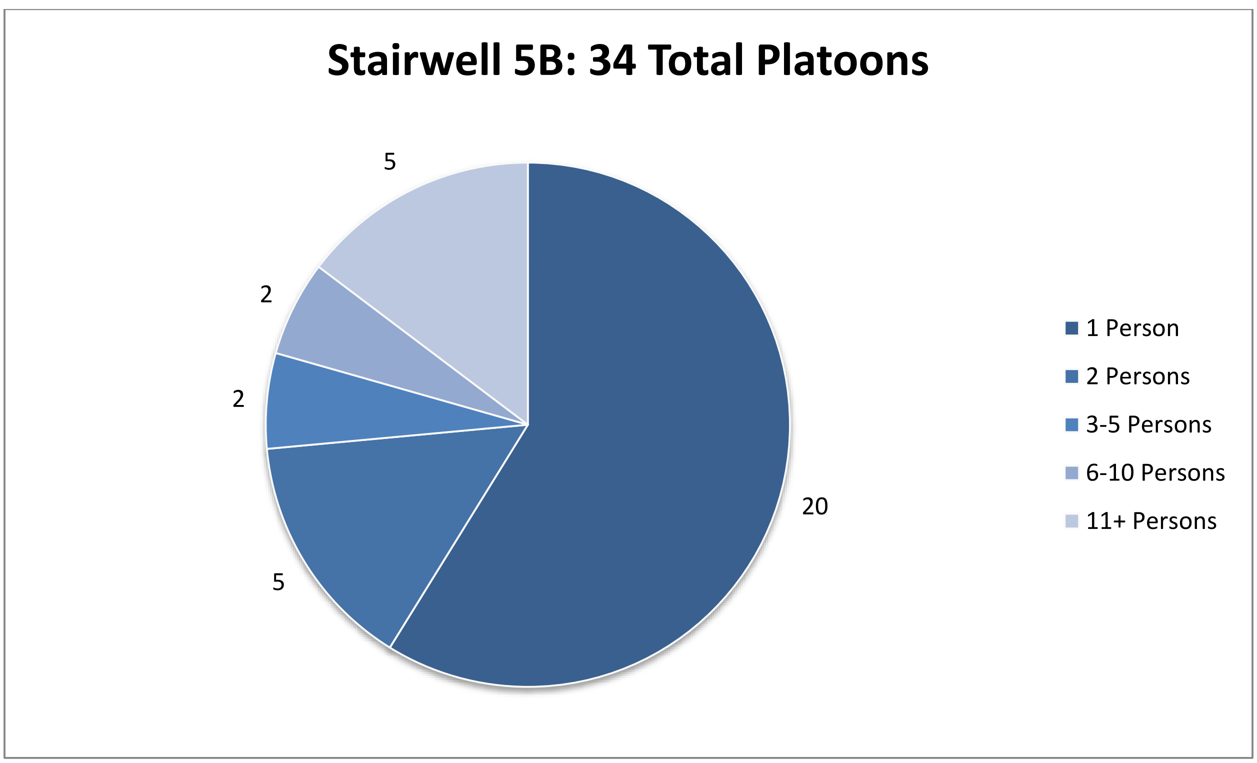

All Stairwells: 331 Platoons
77
107
53
78
Unchanged
Added New Occupants
Merged
Fragmented

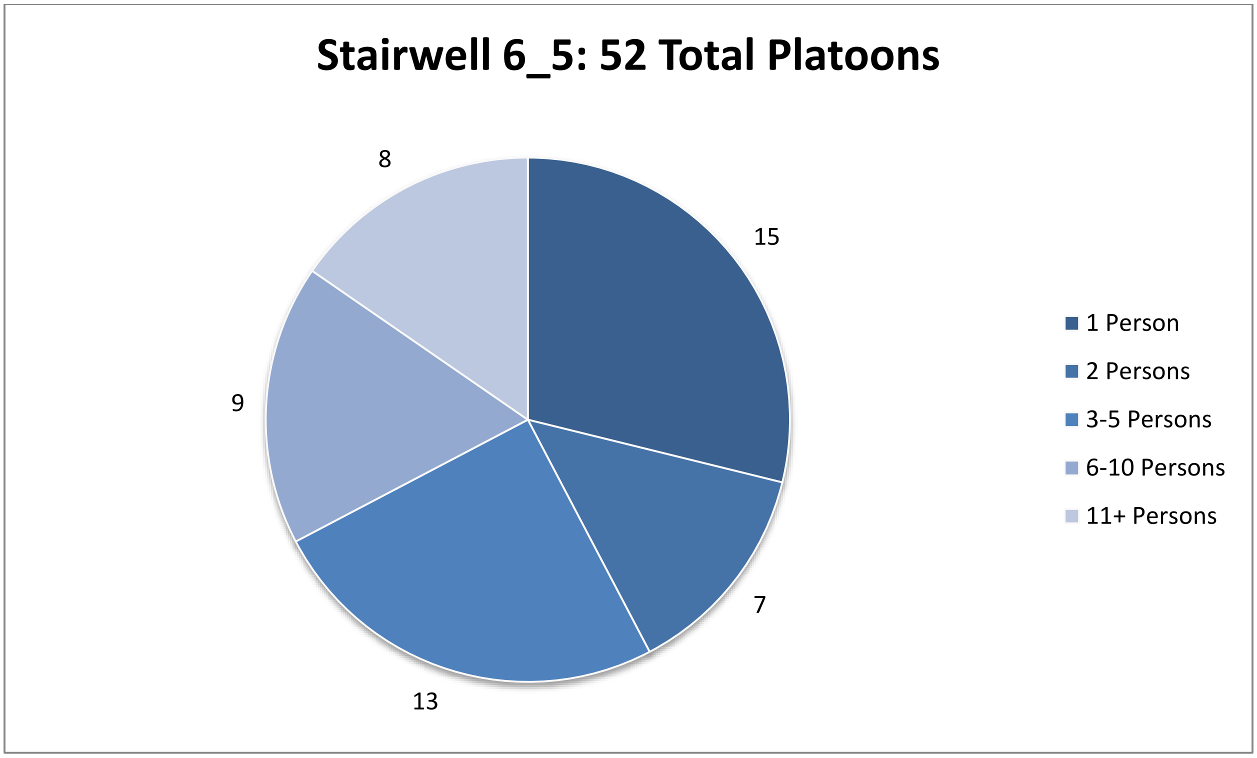
Appendix D: Platoon Size Pie Charts

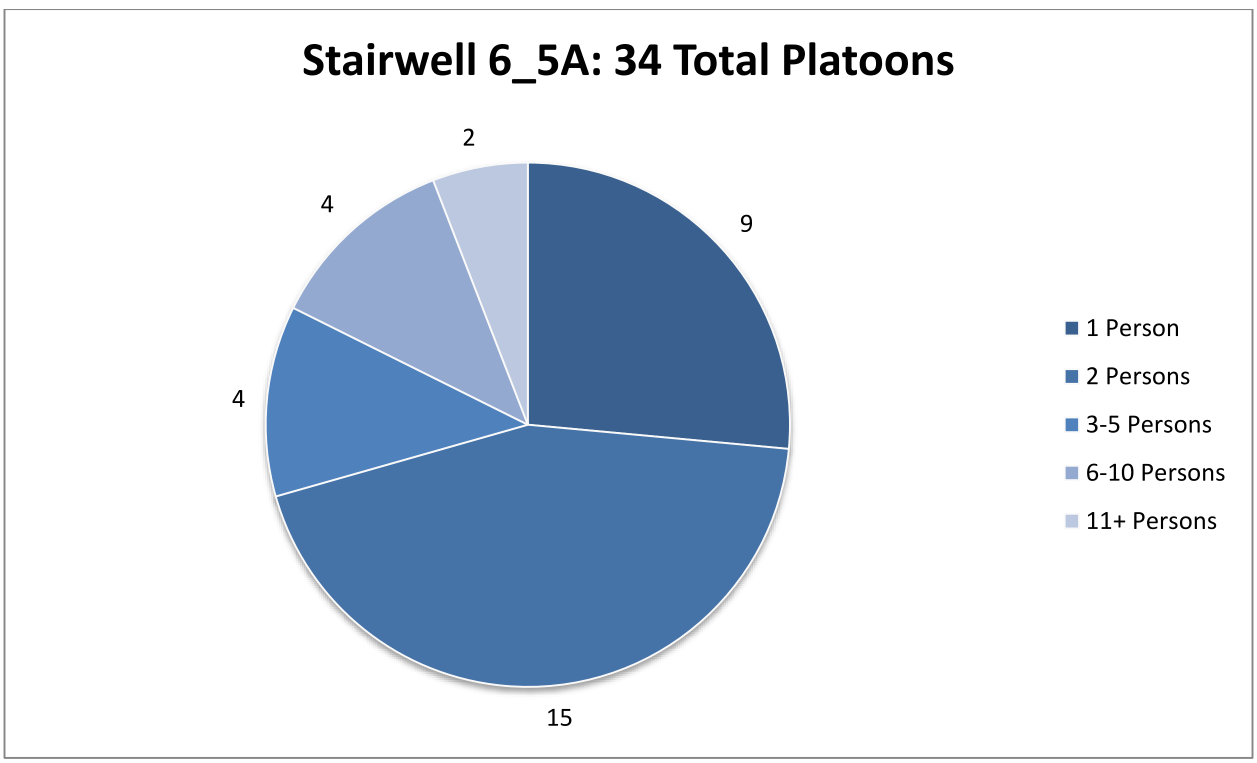


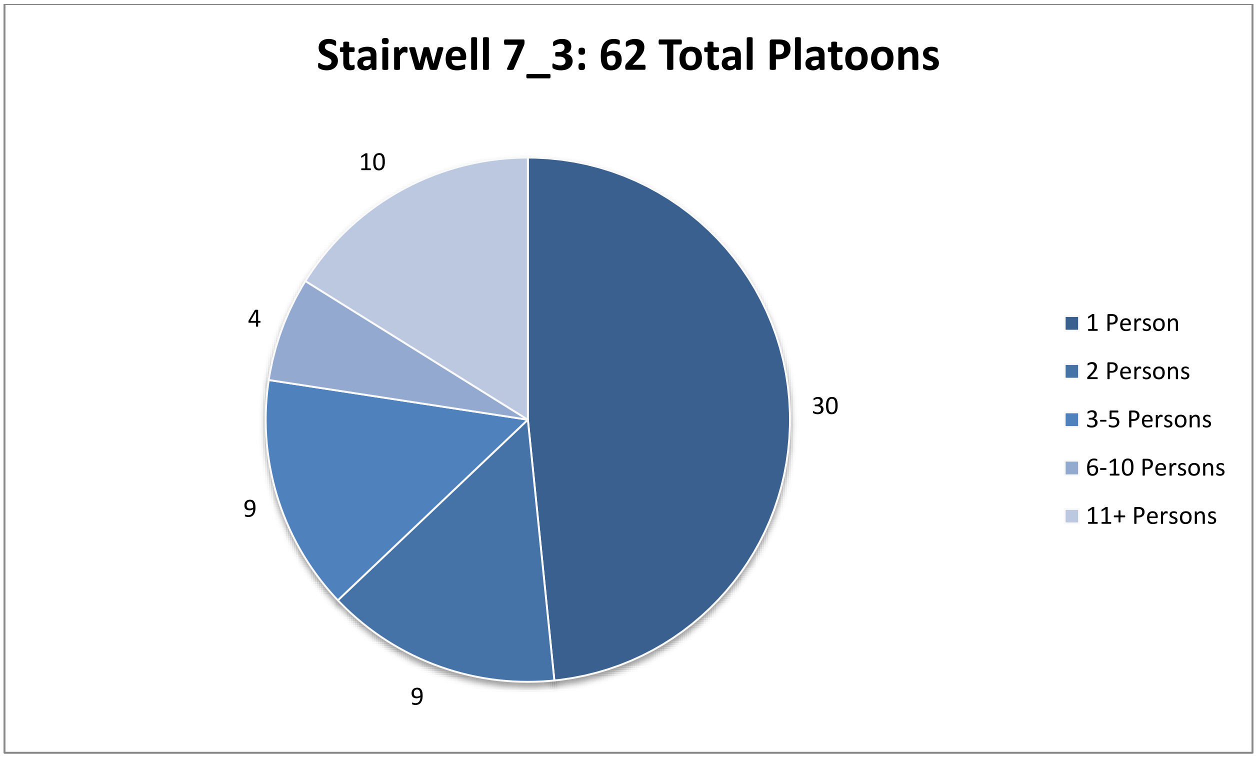


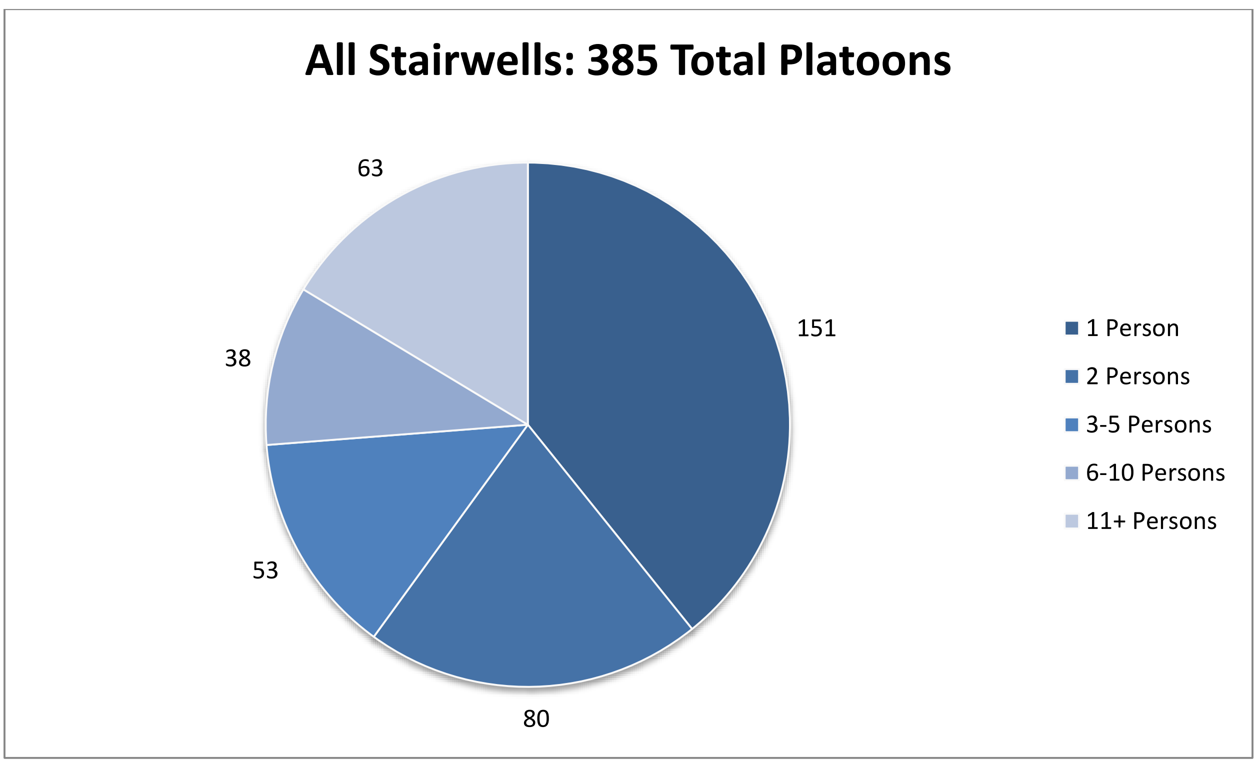

Stairwell 5A: 44 Total Platoons
16
11
5
2
10
1 Person
2 Persons
3-5 Persons
6-10 Persons
11+ Persons


Stairwell 5B: 34 Total Platoons
20
5
2
2
5
1 Person
2 Persons
3-5 Persons
6-10 Persons
11+ Persons


Stairwell 6_5: 52 Total Platoons
8
15
9
7
13
1 Person
2 Persons
3-5 Persons
6-10 Persons
11+ Persons


Stairwell 6_5A: 34 Total Platoons
2
4
9
4
15
1 Person
2 Persons
3-5 Persons
6-10 Persons
11+ Persons


Stairwell 7_3: 62 Total Platoons
10
4
9
9
30
1 Person
2 Persons
3-5 Persons
6-10 Persons
11+ Persons


All Stairwells: 385 Total Platoons
63
38
53
80
151
1 Person
2 Persons
3-5 Persons
6-10 Persons
11+ Persons

References

[1] NFPA, National Fire Protection Association (NFPA), NFPA 101, *Life Safety Code*, Quincy, MA, 2012.

[2] Gwynne, S. and Rosenbaum E., "Employing the Hydraulic Model in Assessing Emergency Movement", *The SFPE Handbook of Fire Protection Engineering, Fourth Edition*, National Fire Protection Association, Quincy, MA, 2008, pp. 3.373-3.396.

[3] Kuligowski, E. D., "Computer Evacuation Models for Buildings", *The SFPE Handbook of Fire Protection Engineering, Fourth Edition*, National Fire Protection Association, Quincy, MA, 2008, pp. 3.456-3.478.

[4] Thunderhead Engineering., "Pathfinder 2011 User Manual."

[5] Latane B. and Darley, J. M., "Group Inhibition of Bystander Intervention in Emergencies", *Journal of Personality and Social Psychology,* Volume 10, 1968, pp. 215-221.

[6] Bryan, J. L., "Behavioral Response to Fire and Smoke," *The SFPE Handbook of Fire Protection Engineering, Fourth Edition*, National Fire Protection Association, Quincy, MA, 2008, pp. 3.320-3.354.

[7] Proulx, G., "Evacuation Time", *The SFPE Handbook of Fire Protection Engineering, Fourth Edition,* National Fire Protection Association, Quincy, MA, 2008, pp. 3.355-3.372.

[8] Pauls, J.L., "A Study of Personnel Evacuation," National Research Council of Canada, Division of Building Research, Ottawa, February, 1975.

[9] Pauls, J.L., and Jones, B. K., "Building Evacuation: Research Methods and Case Studies," in *Fires and Human Behaviour*, John Wiley and Sons Ltd., 1980, pp. 227-249.

[10] Marchant, E. W. (Ed.), *A Complete Guide to Fire and Buildings.* New York: Barnes & Noble Books, 1973.

[11] Masahiro Kagawa, Satoshi Kose, and Yasaburo Morishita, *Movement of People on Stairs during Fire Evacuation Drill- Japanese Experience in a Highrise Office Building*, Building Research Institute, Japan, 1985.

[12] Jones, B. K. & Hewitt, J. A. (1986). Leadership and Group Formation in High-Rise Building Evacuations. In C. E. Grant & P. J. Pagni (Eds.), *Fire Safety Science -- Proceedings of the 1st International Conference* Washington, DC: Hemisphere Publishing Corporation.

[13] Rinne, T., Hostikka, S., Paloposki, T., Korhonen, T., Saari, J.M., and Heliovaara, S., "Application of RFID and Video Imaging on Evacuation Observations in Offices and Public Buildings", *Fire Safety Science, Proceedings of the Ninth International Symposium*, Karlsson, B. (ed.), International Association of Fire Safety Science: London, 2008; pp. 329-340.

[14] Proulx, G., “Evacuation Time and Movement in Apartment Buildings”, *Fire Safety Journal*, Volume 24, 1995, pp. 229-246.

[15] Fahy, R. F. and Proulx, G., “Towards Creating a Database on Delay Times to Start Evacuation and Walking Speeds for Use in Evacuation Modeling”, *Proceedings of the 2nd International Symposium on Human Behavior in Fire, Mass. Inst. of Tech.*, London, Interscience Communications, 2001; pp. 175-183.

[16] Sime, J., "Escape Behaviour in Fires and Evacuations", *Design Against Fire: An Introduction to Fire Safety Engineering Design*, Stollard, P. and Johnston, L., Eds., E & FN Spon: An Imprint of Chapman & Hall, London, UK, 1994, pp. 56-87.

[17] Proulx, G., Reid, I. M. A., & Cavan, N. R. (2004). *Human Behavior Study, Cook County Administration Building Fire, October 17, 2003 - Chicago, IL* (Rep. No. Research Report No. 181). Ottawa, Ontario: National Research Council of Canada.

[18] Galea, E.R. and Blake, S., “Collection and Analysis of Human Behaviour Data Appearing in the Mass Media Relating to the Evacuation of the World Trade Centre Towers of 11 September 2001”, Office of the Deputy Prime Minister, London, UK, 2004.

[19] Shields, T. J., Boyce, K. E., and McConnell, N., “The Behaviour and Evacuation Experiences of WTC 9/11 Evacuees with Self-Designated Mobility Impairments”, *Fire Safety Journal*, Volume 44, 2009, pp. 881-893.

[20] Kratchman, Jessica A., *An Investigation on the Effects of Firefighter Counterflow and Human Behavior in a Six-Story Building Evacuation*, Thesis, University of Maryland, College Park, 2006.

[21] Pushkarev, B. and Zupan, J.M., “Pedestrian Travel Demand,” Regional Plan Association, New York, 1971.

[22] Pushkarev, B. and Zupan, J. M., *Urban Space for Pedestrians*, MIT Press, Cambridge, MA, 1975.

[23] Templer, J. A., *Stair Shape and Human Movement*, Ph.D. Dissertation, Columbia University, 1975.

[24] Gates, T. J., Noyce, D. A., Bill, A. R., and Van Ee, N., “Recommended Walking Speeds for Pedestrian Clearance Timing Based on Pedestrian Characteristics”, Transportation Research Board 85th Annual Meeting Compendium of Papers, November 2005.

[25] M.L. Schiavo, “A Personalized Kinetic Model of Traffic Flow,” Department of Mathematical Models and Methods, Univ. “La Sapienza,” Roma, Italy, 2002.

[26] Robertson, D. I., “TRANSYT Method for Area Traffic Control”, Traffic, Engineering, and Control, Volume 11, Issue 6, 1969, pp. 276-281.

[27] Michalopoulos, P. G., and Pisharody, V., "Platoon Dynamics on Signal Controlled Arterials," University of Minnesota, Minneapolis, Minnesota, 1980.

[28] Shiomi, Y., Yoshii, T., and Kitamura, R., "Platoon-Based Traffic Flow Model for Estimating Breakdown Probability at Single-Lane Expressway Bottlenecks," Department of Civil and Environmental Engineering, Ehime University, Japan, 2009.

[29] Leahy, Andrew P., *Observed Trends in Human Behavior Phenomena within High-Rise Stairwells*, Thesis, University of Maryland, College Park, 2011.

[30] Hoskins, Bryan L., *The Effects of Interactions and Individual Characteristics on Egress Down Stairs*, Ph.D. Dissertation, University of Maryland, College Park, 2011.

[31] Proulx, G., "Movement of People: The Evacuation Timing", *The SFPE Handbook of Fire Protection Engineering, Third Edition*, National Fire Protection Association, Quincy, MA, 2002, pp. 3.342-3.366.

[32] Kuligowski, E. D. and Peacock, R. D., "Building Occupant Egress Data," Report of Test FR4024, National Institute of Standards and Technology, Gaithersburg, MD, 2010.