Evaluation of Factors Addressed by NFPA 101, *Life Safety Code*, that Impact Travel Time in Reaching an Exit

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May 3, 2016

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An Interactive Qualifying Project
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
degree of Bachelor of Science

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Date:
3 May, 2016

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Abstract

Egress factors addressed by NFPA 101, *Life Safety Code*, were investigated to determine which has the greatest impact on occupant travel time in reaching an exit on a floor. Literature searches, application of NFPA 101, observations of occupant movement, calculation techniques and Pathfinder, a computer-based egress simulation program, were implemented. Factors were evaluated for various building configurations within the maximum allowable NFPA 101 limits. Egress factors were quantified and ranked, and recommendations on factors not articulated in NFPA were addressed.

Executive Summary

During a fire event, numerous decisions can be made by building occupants that impact the time it takes them to reach a building exit. NFPA 101, *Life Safety Code*, was developed to improve fire safety and help prevent the loss of life from fires by setting specific limitations on building features and requiring other certain provisions. However, NFPA 101 does not specifically address the time needed for occupants to reach an exit on a floor and be considered safe by the code. The purpose of our project was to assess the range of factors addressed by NFPA 101 to determine which has the greatest impact on an occupant's travel time in reaching a building exit.

We approached the project by identifying factors influencing travel times for analysis, , determined travel speed information through literature searches and field observations, and calculated travel times for a range of building floor plan layouts with respect to the identified factors using techniques documented in the SFPE Handbook of Fire Protection Engineering and the computer-based egress simulation program Pathfinder.

Due to the broad range of human behaviors that could be encountered, detailed analysis of travel time in fire situations is difficult to access using only the SFPE egress calculation technique. However the technique helped us gain a better understanding of the issues and set a basis for more indebt analysis of the relevant factors.

Pathfinder was used as it could consider occupant movement and travel times for various building floor plan layouts. The first floor of Higgins Laboratories, a building on the WPI campus, formed the basis for the floor plan layouts. Different layouts representing the egress factors set to the maximum limitations of NFPA 101 were modeled and evaluated.

Pathfinder allows for two modes of occupant movement, SFPE mode and Steering mode, both of which were used in calculating travel time data. Scenarios representing each egress factor individually and collectively were analyzed. This analysis also prompted a closer examination of the development and impact of queue times in reaching the exit.

As a result of our project, we determined that occupant load has the greatest impact on travel time, followed by travel distance to exit, number of exits, door width, hallway width, and common path of travel. Based on the dimensional limitations of NFPA 101, occupants are allowed up to 500.7 seconds to reach an exit on a floor for the building scenarios evaluated.

Further we recommend additional considerations for supplementary development of travel time calculations. We recommend varying the average walking speed of the occupants to account for characteristics such as ability, gender, and age. Next we recommend analyzing both the derivation of the SFPE hand calculation model and the simulation algorithms of Pathfinder so as to incorporate additional factors into these calculation methods.

Authorship

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Acknowledgments

Our team would like to thank our advisor Professor Milosh Puchovsky for his help and guidance throughout the entirety of the project. Thank you for continually answering our questions and providing feedback on the work we completed. The work and time Professor Puchovsky put into advising the project was indispensable.

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Terminology

Ability - The possessions of a means or skill to do something
Aisle - A passage between rows or seats in a building
Aisle Accessway - The initial portion of the exit access that leads to an aisle.
Boundary Layer - The clearance needed to accommodate lateral body sway and assure balance
Calculated Flow – The predicted flow rate of person's passing a particular point in an exit route
Disability - The consequence of an impairment that may be physical, cognitive, mental, sensory, developmental, or some combination of these that result in restrictions in an individual's ability to participate in what is considered normal in their everyday society
Effective Width - The clear width of an exit path less the width of the boundary layer
Exit - That portion of a means of egress that is separated from all other spaces of a building or structure by construction or equipment as required to provide a protected way of travel to the exit discharge
Exit Access - That portion of a means of egress that leads to an exit
Exit Discharge - That portion of a means of egress between the termination of an exit and the public way
Flow - The rate at which occupants pass a particular point per unit of time
Governing Flow – The lowest calculated flow rate within in an egress route that limits the flow rate of all prior flows in the egress route
Means of Egress - A continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three separate and distinct parts: (one) the exit access, (two) the exit, (three) the exit discharge
Net Area - The floor area within the inside perimeter of the outside walls, or the outside walls and occupants with each other and with boundaries
Occupiable Area- An area of a facility occupied by people on a regular basis
Queue Time – The time an occupant spends at a standstill in an egress route
SFPE Mode - Agents use behaviors that follow SFPE guidelines, with density-dependent walking speeds and flow limits to doors, but do not prevent multiple persons occupying the same space
Specific Flow – The flow rate per unit of effective width
Steering Mode – Agents proceed independently to their goal, while avoiding other occupants and obstacles. Door flow rates are not specified but result from the interaction of occupants with each other and with boundaries

1. Introduction

In the case of an emergency, it is important that occupant egress happens in an efficient and timely manner. In this regard, NFPA 101 Life Safety Code (NFPA 101) was created 1913 to improve life safety during a fire. NFPA 101 contains provisions pertaining to building features and operational procedures to assure a safe and efficient egress, and has been revised many times due to tragic fires and new information that has become available.

There are multiple factors that influence means of egress. NFPA 101 addresses many of these factors including travel distances to exits, number of exits, door and hallway widths, occupant load, blocked and obstructed pathways, building occupancy and geometry, and lighting and exit signs. Travel distance to an exit is the distance the occupant has to reach an exit and be considered safe. Common path of travel pertains to the travel path along which occupants do not have a choice in reaching an exit. The number of exits is stated to provide more than one means of egress. Measurements of the doors, hallways and aisle ways affect the flow of occupants as they evacuate. Blocked or obstructed pathways can affect means of egress of occupants, forcing either a slower flow of movement or forcing the occupants to choose another path. The building occupancy characterizes the general use and type of occupants in a building or portion of a building. The building used for our project, Higgins Labs, is classified as an assembly and business occupancy per NFPA 101. The NFPA 101 requires emergency lighting for evacuation, and exits must be clearly marked by an approved sign.

There are also factors that affect the means of egress that are not specifically covered by NFPA 101, including pre-evacuation time, travel speed, route choice, and flow conditions. Pre-evacuation time includes the awareness of the occupants, the threat level the occupants sense, behavior tendencies of the occupants, and the level of knowledge occupants have of their surroundings and emergency evacuation procedures. Travel speed can be affected by the abilities and disabilities of occupants as well as physical building factors. The route choice of an occupant can depend on the occupant's familiarity with the building and their knowledge of the best route for the most efficient egress. The flow condition of the crowd exiting a building is a factor of density and speed of the crowd.

The goal of our project is to assess which factors influencing means of egress as addressed by NFPA 101 have the strongest impact on the time needed to reach an exit on a given floor, and to assess the maximum amount of time allowed by NFPA 101 to safely reach an exit on a floor. In order to make these assessments our team completed observations of walking speed and occupant egress of certain facilities on the WPI campus, performed hand calculations to determine travel speeds and evacuation times for certain scenarios, and used the egress modeling program Pathfinder to better assess how each factor affects occupant evacuation. For our project, our team utilized the first floor of Higgins Laboratories on the WPI campus. Pathfinder was used to simulate occupant egress for a range of building configurations based on the Higgins Laboratories. The configurations consisted of the current floor plan, the floor plan modified with applicable building dimensions (factors) set to the maximum values permitted by NFPA 101, and other modified floor plans with each individual factor addressed by NFPA 101 set to its maximum value.

2. Background

In order to first understand the importance of our project, we will discuss in this section:

2.1 History of the NFPA 101 Life Safety Code
2.2 Overview of Means of Egress Concepts
2.3 All Factors Affecting Occupant Means of Egress
2.4 Factors Affecting Occupant Means of Egress Addressed by NFPA 101
2.5 Factors Affecting Occupant Means of Egress Not Addressed by NFPA 101

2.1 History of the NFPA 101 Life Safety Code

The NFPA 101 Life Safety Code (NFPA 101) was created in 1913 to address "construction, protection, and occupancy features necessary to minimize danger to life from the effects of fire, including smoke, heat, and toxic gases created during a fire."[11] Over the years NFPA 101 has had many changes made to it, and today it particularly deals with "hazards to human life in buildings, public and private conveyances and other human occupancies, but only when permanently fixed to a foundation, attached to a building, or permanently moored for human habitation"[11]

Several events throughout history have caused NFPA 101 to be significantly modified and updated. A specific example of such a fire incident that led to a change of NFPA 101 was the Coconut Grove Nightclub Fire in November of 1942.[12] The club was packed with roughly 1000 people on a Saturday night after a rival football game in Boston, Massachusetts. The fire began in the basement lounge between the cloth and plywood ceiling, and ascended up the stairway. There was a door for the employees to use as a passageway from the basement into the kitchen, however the exit door leading outside from the kitchen was locked the night of the fire, trapping the occupants. The fire then moved from the stairs into the connecting corridor. Another exit door leading outside at the end of the hallway was also locked the night of the fire. The fire made it to the street level outside the lobby in just four minutes after the first witness sighting. The result was 492 deaths and a desperate need to reform the life safety code. NFPA 101 reclassified restaurants and nightclubs as places of public assembly, which created stricter regulations.[12]

A more recent event that affected the life safety code was the collapse of the World Trade Center in September of 2001. In the rush to egress as many occupants as possible, firefighters had difficulty getting up the stairs with their equipment while others were trying to descend down, ultimately slowing the flow of occupants to the exit. In 2006, the code increased the minimum stair width from 44 inches to 56 inches when occupant load exceeds 2,000 persons.[3]

The technical committees responsible for NFPA 101 continuously work to improve and address factors relating to means of egress in order to provide occupants a reasonable degree of safety.

2.2 Overview of Means of Egress Concepts

Means of egress is defined by NFPA 101 as "a continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three separate and distinct parts: the exit access, the exit, and the exit discharge."[11] Numerous physical components of the building within the means of egress are regulated by NFPA 101. These regulations are intended to provide sufficient time and available facilities for occupants to safely egress a building.

2.3 Range of Factors Affecting Occupant Means of Egress

NFPA 101 regulates numerous factors affecting the means of egress. However for various reasons, certain aspects of egress during fire are not specifically addressed by regulations such as NFPA 101. Our group defined a range of factors affecting means of egress as follows:

- Travel Distances to Exits
- Common Path of Travel
- Number of Exits
- Door Width
- Hallway Width
- Occupant Load
- Blocked vs Obstructed Pathway
- Occupancy Classification
- Lighting/Exit Signs
- Pre-Egress Time
- Travel Speed
- Route Choice
- Flow Conditions

2.4 Range of Factors Affecting Means of Egress Addressed by NFPA 101

Our group defined the factors addressed by NFPA 101 affecting means of egress from what we consider the least to the greatest influence based on our prior understanding of egress situations in the following order:

- Lighting/Exit Signs
- Occupancy Classification
- Blocked vs Obstructed Pathway
- Occupant Load
- Hallway Width
- Door Width
- Number of Exits
- Common Path of Travel
- Travel Distances to Exits

A description of each of the factors as addressed by NFPA 101 is provided below in the same order as stated above.

- Lighting/Exit Signs

An emergency exit symbol is regulated to a minimum of 4 inches in height and must be applied on or above the door, centered horizontally, with the top of the symbol not higher than 18 inches above the floor. Exits should be marked with approved signs that are visible from any direction of the exit access. There is to be no decorations, furnishings or equipment that could impair the visibility of the sign, or anything that could potentially detract attention from the exit sign. These signs will help occupants who are unfamiliar with the building layout locate an exit quickly. The common path of travel must be clearly marked by an approved sign visible from any direction from a distance of 40 ft. Visibility of the aisle within an assembly occupancy is also an important factor affecting how an occupant moves to an area of safety. NFPA 101 requires all aisles provide a contrasting marking along treads where its location is not always readily apparent. For our project, the simulations and hand calculations are unable to account for these factors.

- Occupancy Classification

NFPA 101 sets different provisions based on a specific occupancy of the building, which qualifies both the types of occupants expected to be present and the nature of the operations conducted within the building. Examples of such occupancies addressed by Chapter 6 of NFPA 101 is as follows:[11]

➢ *Business Occupancy*- an occupancy used for the transaction of business other than mercantile.

➢ *Educational Occupancy*- an occupancy used for educational purposes through the 12th grade by six or more persons for 4 or more hours per day or more than 12 hours per week.

➢ *Day Care Occupancy*- an occupancy in which four or more clients receive care and supervision, by other than their relatives or legal guardians, for less than 24 hours per day.

➢ *Assembly Occupancy*- an occupancy used for a gathering of 50 or more persons for deliberation, worship, entertainment, eating, drinking, amusement, awaiting transportation, or similar uses.

➢ *Residential Occupancy*- places providing sleeping accommodations for purposes other than health care or detention and correctional.

➢ *Health Care Occupancy*- used to provide medical or other treatment or care simultaneously to four or more patients on an inpatient, where such patients are mostly incapable of self-preservation due to age, physical, or mental disabilities or because of security measures not under the occupants' control.

Each occupancy has different requirements based on the type of occupants. For example, taking into consideration the average age and size of occupants in different educational occupancies, NFPA 101 requires that rooms normally occupied by preschool, kindergarten, and first grade students are located on a level of exit discharge. This is in place in attempt to prevent the small occupants from becoming trampled while trying to reach the exit.

- Blocked vs. Obstructed Pathway

A blocked pathway is deemed unusable, while an obstructed pathway is usable because there is at least one exit is still accessible. Obstructions include anything existing or projecting into the pathway beyond the limits of NFPA 101. The arrangement of the means of egress is important because the goal is to minimize the possibility that more than one pathway becomes blocked and unusable. Therefore, exits, exit accesses, or exit discharges are to be remotely located from each other. For example in many educational occupancies, reaching the exit requires navigating the numerous obstacles in the room, slowing down travel speed.[11] Doors opening into the exit access corridor are arranged such that they do not impede or obstruct travel through the exit access corridor. For our project we did not test simulations of blocked or obstructed pathways because it is difficult to emulate the placement of the fire and the many different obstructions that could occur during a fire.

- Occupant Load Factor

NFPA 101 outlines the number of occupants, otherwise known as the occupant load, allowed in an area using the occupant load factor for any given occupancy. The maximum occupant load is determined by dividing the gross or net area of the floor by the occupant load factor specific for each occupancy as defined by Table 1 below.[11] The gross floor area is defined by NFPA 101 as “The floor area within the inside perimeter of the outside walls of the building under consideration…”[11] The net area is defined by NFPA 101 as “The floor area within the inside perimeter of the outside walls of the building under consideration with deductions for hallways, stairs, closets, thickness of interior walls, columns, and other features”[11] Exceeding the maximum occupant load of any room increases the population density and the amount of time needed for all occupants to reach a place of safety, increasing the level of danger in Higgins Labs.

Table 1: Occupant Load Factors

Use	(ft²/person)[a]	(m²/person)[a]
Assembly Use		
Concentrated use, without fixed seating	7 net	0.65 net
Less concentrated use, without fixed seating	15 net	1.4 net
Bench-type seating	1 person/18 linear in.	1 person/455 linear mm
Fixed seating	Use number of fixed seats	Use number of fixed seats
Waiting spaces	See 12.1.7.2 and 13.1.7.2.	See 12.1.7.2 and 13.1.7.2.
Kitchens	100	9.3
Library stack areas	100	9.3
Library reading rooms	50 net	4.6 net
Swimming pools	50 (water surface)	4.6 (water surface)
Swimming pool decks	30	2.8
Exercise rooms with equipment	50	4.6
Exercise rooms without equipment	15	1.4
Stages	15 net	1.4 net
Lighting and access catwalks, galleries, gridirons	100 net	9.3 net
Casinos and similar gaming areas	11	1
Skating rinks	50	4.6
Business Use (other than below)	100	9.3
Concentrated Business Use[f]	50	4.6
Air traffic control tower observation levels	40	3.7
Day-Care Use	35 net	3.3 net
Detention and Correctional Use	120	11.1
Educational Use		
Classrooms	20 net	1.9 net
Shops, laboratories, vocational rooms	50 net	4.6 net
Health Care Use		
Inpatient treatment departments	240	22.3
Sleeping departments	120	11.1
Ambulatory health care	100	9.3
Industrial Use		
General and high hazard industrial	100	9.3
Special-purpose industrial	NA	NA
Mercantile Use		
Sales area on street floor[b,c]	30	2.8
Sales area on two or more street floors[c]	40	3.7
Sales area on floor below street floor [c]	30	2.8
Sales area on floors above street floor[c]	60	5.6
Floors or portions of floors used only for offices	See business use.	See business use.
Floors or portions of floors used only for storage, receiving, and shipping, and not open to general public	300	27.9
Mall buildings[d]	Per factors applicable to use of space[e]	
Residential Use		
Hotels and dormitories	200	18.6
Apartment buildings	200	18.6
Board and care, large	200	18.6
Storage Use		
In storage occupancies	NA	NA
In mercantile occupancies	300	27.9
In other than storage and mercantile occupancies	500	46.5

- Hallway Width

The width of hallways is measured at the narrowest point and must be a minimum of 44 inches. Wider hallways provide more room for occupants to travel on their way to the exit allowing for a greater occupant flow and a faster travel time.

- Door Width

Every door opening that is used for an exit must have a path that is obvious and direct. Door openings in means of egress are regulated to a width of at least 32 inches wide. The width of the door opening is taken at the narrowest point when the door is fully open, and does not project more than 7 inches into the required width of an aisle. Door leaves must be arranged so that they can be readily opened from the egress side whenever the building is occupied. The door widths affect the flow rate of occupants, which influence the time it takes for egress.

- Number of Exits

The specific number of exits and their location relative to one another is defined in NFPA 101 based on building layout and the occupant load in an attempt to provide an accessible means of egress for all occupants. All room exits must be located in a way that they are readily accessible at any instant. According to NFPA 101, a minimum of two exits is required, where there is a distance no more than half the maximum diagonal of the building or the area between the two exits. This number may increase based on the occupant load of the assembly area. For example, if the occupant load is between 500 and 1000 occupants, the minimum number of room exits is increased from two to three. The number of exits is increased again from three to four if the occupant load is greater than 1000 occupants. Having multiple exits prevents occupants from being trapped when one exit is blocked, in addition to controlling the outward flow by dispersing exiting occupants through numerous exits. A single exit is allowed for a two story building that contains an approved sprinkler system and has a total travel distance no more than 100 ft. Exit doors cannot be locked beyond the occupant’s control except in specified occupancies such as detention and correctional facilities and health care occupancies. For our project we adjusted the number of exits to evaluate their influence.

- Common Path of Travel

The common path of travel refers to an area of the exit access where occupants from different rooms must travel along the same path in order to reach a point at which paths to different exits become available. For our project the common path of travel was only applicable to the business occupancies.

- Travel Distance To Exits

The travel distance to an exit is measured along the centerline of the natural path of travel and curve around any corners or obstructions with a 12-inch clearance. The travel distance is the total distance that must be traveled for egress, including the common path of travel. Travel distance can vary based on whether or not the building is equipped with an approved sprinkler system. If the occupancy has a sprinkler system, the travel distance is extended. The sprinklers will be able to control the fire, thus allowing a longer travel distance. For our project the distance the occupant has to travel affected the travek time of occupant egress.

2.5 Range of Factors Affecting Occupant Means of Egress Not Addressed by NFPA 101

While NFPA 101 addresses the factors that impact a building's physical dimensions and characteristics, it does not specifically address factors associated with occupant movement speed and decision making. Below is a list of the factors of means of egress and their description that NFPA 101 does not explicitly address:

- Pre-Egress Time
    - Awareness/Threat Level
    - Behavior Tendencies
    - Previous Knowledge of Surroundings and Procedures
- Travel Speed
- Route Choice
- Flow Conditions

- **Pre-Egress Time**

The time it takes occupants to initiate a response and begin moving to a place of safety is the pre-egress time.[8] This is the time period where the occupant makes decisions based on his or her alertness, personality, behavior, and beliefs. Each of these factors contributes to the time required for the occupant to become aware of the danger and make a decision on how to respond based on the intensity of danger.

  - **Awareness/Threat Level**

In many events, the realization of danger does not occur instantaneously upon the initial instance of danger and therefore greatly impacts the time required to reach a point of safety. At a time of danger, occupants must first become aware of the present danger. This can be done through visible danger, person to person interaction, or by the discovery of danger by an occupant's own sensory knowledge. When signals are used to notify occupants of danger, the recognition of danger varies between occupants. Many factors, including signal volume, signal tone, signal location, occupancy alertness, occupancy knowledge of signals, and time of day, control the rate at which occupants become aware of the danger signal. There are numerous signaling techniques that are implemented to spread awareness of a fire. NFPA 101 generally requires some type of fire alarm system in most occupancies. However, the perception of danger based on the fire alarm signal can differ among occupants.[8] An occupant's cognitive awareness can drastically affect the physical response to a fire signal. If fully awake and alert of the surroundings, occupants have a much greater chance of hearing the fire signal and comprehending the associated danger. Given the opposite situation where occupants may not be fully awake or aware of all surroundings, recognition of danger due to a fire signal may be dramatically delayed. This delay affects the pre-egress time, ultimately increasing the time to reach safety.

  - **Behavior Tendencies**

After signal recognition, the next issue becomes response behavior. Response behavior is directly related to the understanding of danger and the personality of the occupant.[8] The response can range from being instantaneous to delayed from the time of recognition of danger. Once the decision is made to egress toward a place of safety, other human behaviors may continue to delay the physical progression. If the occupant begins to egress toward the exit without hesitation, he or she is acting in a way that minimizes time needed to egress. In contrast, the occupant increases the time required to reach safety if upon recognition of danger he or she attempts to gather personal belongings or other physical accessories. For our project, there was no real way to properly assess occupant's pre-egress behavior; therefore it was assumed that each occupant reacted at the first signal of egress.

- **Previous Knowledge of Surroundings and Procedures**

An occupant's reaction to danger is dependent on both past and present experiences. Occupants with experience in fire situations or proper training may react in a timelier manner but delay his or her own egress to aid the safe egress of others. For occupants experiencing a fire situation for the first time, or are in an unfamiliar occupancy, their reaction to the fire may be delayed due to underestimating the danger present or because they are unaware of how to reach safety. Due to the computer simulation aspect of the project, factors concerning human knowledge were not specifically evaluated.

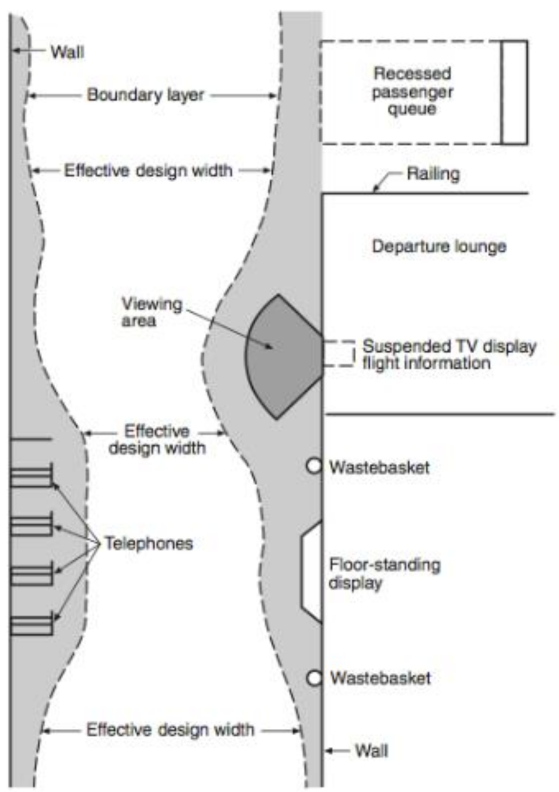
- **Travel Speed**

The travel speed refers to the rate at which occupants are able to move through the building and can vary based on the situation.[8] In a normal condition the area has clear and visible pathways and occupants moves at "usual maximum speed and there are no [disabled] occupants."[13] However, it is important to consider how different situations affect the travel speed. Multiple queue times were observed in Higgins Labs affecting the travel speed and increasing the time to egress.

A disability can be defined as a physical or mental condition that limits an occupant's movements, senses, or activities from that of an able-bodied occupant. For occupants with a permanent or temporary disability, extra time is needed to reach a point of safety. The travel speed of occupants with disabilities is slower than able-bodied occupants, resulting in longer travel time in an emergency. Multi-directional movement is hindered for an occupant with a disability, causing difficulty when turning corners and ascending and descending stairs in egress toward an exit. These situations will cause a delay in the person's egress to safety. Lack of stamina is also a concern with travel time. If the occupants tire easily, their travel speed will decrease as they travel to the exit, and they may need to stop momentarily to rest. These factors will increase the time needed for the occupant to reach safety. For our project we assumed that all occupants were able-bodied occupants.

During egress, abnormal or chaotic movement types can occur. Natural movement tendencies include lateral body sway.[8] As a result; an increased required width must be accounted for when determining a minimum effective width. Referring to the net usable width, effective width must provide sufficient room for natural movement tendencies as well as required and observed boundary widths. During egress, natural movement through an exit access will not occupy the entire floor area. The boundary layer encompasses all areas in which occupants naturally avoid, including but not limited to areas around obstacles and areas along walls as seen in Figure 1.[8] Pathfinder accounts for a boundary layer of 0.08 meters for each occupant during simulation. The value is independent of the width limitations of NFPA 101.

Figure 1 "Public Corridor Effective Width



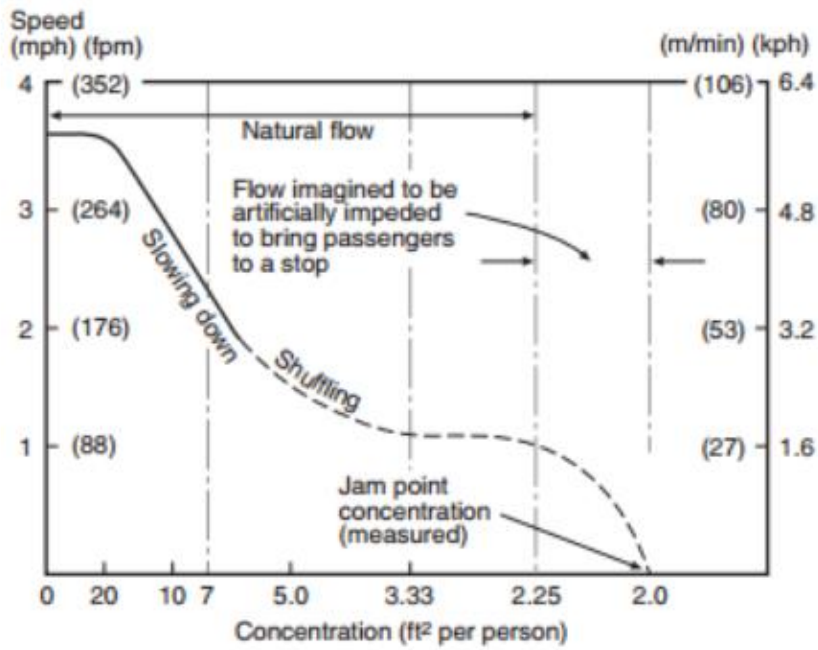
- **Route Choice**

Occupants who are familiar with the building layout and the egress route to the nearest exit will be able to exit in a timely manner during a normal condition.[13] However, occupants who are unfamiliar with the building may not be aware of the building layout and therefore may not choose the shortest route to exit the building. This would cause a delay in the time it takes to safely reach the exit if the occupant gets lost and has to backtrack to find the correct route. While NFPA 101 regulates the use of exit signs, ultimately human behavior determines route choice. During simulations it was observed that occupants actively went to the closest exit, illustrating prior knowledge of the exit locations. During the physical observations of students exiting Higgins Labs, it was clear that they also had prior knowledge of the building exits.

- **Flow Conditions**

Flow is the rate at which occupants pass a particular point in the egress route per unit of time.[8] The flow rate, along with occupancy density and speed, directly affects the travel time to the exit. The density of occupants in any area of the building has an impact on flow rate and the time needed to escape to an area of safety. Natural human behavior plays an important part in how occupant density affects flow rate. In general, occupants establish "territories."[8] When occupants begin touching one another, the risk of injury due to other occupants significantly increases. Also, at points where the occupant density increases and the flow rate significantly decreases, shuffling beings, as shown in Figure 2.[8] The speed at which the crowd egress in an emergency is a function of the density. If density exceeds 0.5 person/ft^2 there will be no movement until the crowd moves out of the congested area and the density is reduced. The maximum speed is reached when the density of the crowd is less that 0.05 person/ft2 as seen in Figure 2.[8] The travel speed affects the time needed to egress.

Figure 2: Speed in Level Passageways



3. Methodology

The goals of our project were to determine which factors of means of egress have the biggest impact on travel time and to assess the maximum amount of time needed to safely reach the exit of an occupancy based on the dimensional limitations of NFPA 101. In order to reach this goal, we applied and analyzed NFPA 101, previous research data, observations, calculations, and computer simulation software. We approached the project in the following manner:

- 3.1 Considered Factors for Sensitivity Tests in Pathfinder
- 3.2 Searched Walking Speed Studies
- 3.3 Observations
    - 3.3.1 Observed Walking Speeds
    - 3.3.2 Observed Assembly Occupancy
- 3.4 Floor Plan Calculations
    - 3.4.1 Calculated Travel Time of Higgins Labs 116
    - 3.4.2 Calculated Travel Time of Higgins Labs Hallway to Floor Exit 1
    - 3.4.3 Limitations of Hand Calculations
- 3.5 Application of Pathfinder
    - 3.5.1 Description of Pathfinder
    - 3.5.2 Modeled Higgins Labs 116 in Pathfinder
    - 3.5.3 Usefulness of Pathfinder
    - 3.5.4 Modeled Higgins Labs First Floor in Pathfinder
    - 3.5.5 Applied Relevant NFPA 101 Dimensional Limitations in Pathfinder
    - 3.5.6 Simulated Scenarios of Higgins Labs in Pathfinder
    - 3.5.7 Limitations of Pathfinder
    - 3.5.8 Calculated Queue Time

3.1 Considered Factors for Sensitivity Tests in Pathfinder

The factors previously stated in section 2, addressed by NFPA 101, that influence travel time are listed in the order we believed to have an increasing effect:

- Lighting/Exit Signs
- Occupancy Classification
- Blocked vs Obstructed Pathway
- Occupant Load
- Hallway Width
- Door Width
- Number of Exits
- Common Path of Travel
- Travel Distances to Exits

These were the factors chosen as related to the egress travel time because they govern the distance that needs to be covered by the occupant; the available paths the occupant may take to reach safety, and the space the occupant have to maneuver. All of the factors listed above contribute to the time it takes occupants to safely reach an exit in a fire situation. For our project, the following NFPA 101 dimensional limitations were considered when analyzing the time of egress:

- Maximum Occupant Load
- Minimum Hallway Width
- Minimum Door Width
- Minimum Number of Exits
- Maximum Common Path of Travel
- Maximum Travel Distance to Exit

3.2 Searched Walking Speed Studies

In order to properly calculate the occupant flow within the means of egress, we needed to explore an occupant's average travel speed. A literature search was initially conducted to try to determine an average walking speed. A study at Portland State University was conducted in 2005 to determine the average crossing speed of younger and older pedestrians,[2] where older pedestrians were defined as 60 years of age and above. The study, recorded at eight separate Portland locations varying in crossing distances and traffic flow, recorded 100 crossing times using a handheld stopwatch. Gender, age, group size, signal compliance, initial speed, and pace consistency were all taken into consideration as shown in Table 2 below.

Table 2: Summary of Mean and 15th Percentile Walking Speeds in ft/s for Younger and Older Pedestrians

Factors	Number		Mean		15th Percentile	
	Older Peds	Younger Peds	Older Peds	Younger Peds	Older Peds	Younger Peds
GENDER						
Female	99	298	4.15	4.73	3.34	3.95
Male	95	323	4.52	4.96	3.74	4.18
GROUP SIZE						
Alone	120	331	4.38	5.04	3.43	4.21
With Others	74	292	4.26	4.63	3.60	3.94
SIGNAL COMPLIANCE						
Start on Walk	154	493	4.30	4.81	3.47	4.05
Start on Flashing Don't Walk	38	130	4.44	5.01	3.71	4.20
INITIAL SPEED						
Stopped	130	381	4.21	4.75	3.30	4.05
Walking	67	243	4.58	5.00	3.91	4.11
PACE CONSISTENCY						
Pace change	6	32	4.61	5.36	3.60	4.28
No pace change	188	592	4.32	4.82	3.51	4.06

Another study we focused on was a Japanese study of the travel speed of the users of two shopping centers.[7] The results are shown in Table 3 below.[7] The study tracked people varying in age, disability, and whether they were in a group or alone. The "able-bodied adult walking with another person,"[7] is the closest relatable category to the students we observed at WPI. We chose these two studies in order to compare both indoor and outdoor settings and their effect on walking speed. These observations are described in section 3.3.

Table 3: Average Walking Speeds for Various Users of Two Shopping Centers

User Category	Average Walking Speed (m/sec)	Standard Deviation (m/sec)	N
Adult with difficulty walking			
Older adult walking very slowly	0.83	0.20	21
Adult with walking disability	0.78	0.19	8
Pregnant woman	0.79	0.12	4
Adult with child, baby, or toddler	0.93	0.33	171
Adult with child and baby or toddler	0.88	0.26	25
Adult with baby or toddler	0.90	0.24	77
Adult with child	1.00	0.41	69
Older adult	0.93	0.22	155
Older adult with another person	0.88	0.23	49
Older adult walking alone	0.96	0.22	103
Able-bodied adult			
Walking with another person	0.93	0.25	314
Walking alone	1.14	0.27	446
Total	1.03	0.29	937

Source: Interscience Communications

3.3 Observations

Our next step was to investigate walking speeds at certain locations across the Worcester Polytechnic Institute (WPI) campus. We measured, observed, and recorded the walking speed of the students in an outdoor setting at WPI as well as the egress travel time for occupants inside a WPI building.

3.3.1 Observed Walking Speeds:

Our group wanted to compare the average walking time of individuals we found from previous studies to the students on the WPI campus. We met mid day at the WPI campus fountain to find the average walking speed of students when traveling between classes. We measured the distance across the fountain from opposing openings to be 50ft, as well as the diagonal distances between adjacent openings to be 29ft, as seen in Figure 3 below. Using a handheld stopwatch, we measured the time it took various people to walk either the 50ft straight across the fountain or the 29ft diagonally through the fountain area, starting the stopwatch as they entered the entrance between benches for a total of 30 minutes. These times are not representative of a fire egress situation due to the lack of building restrictions in an outdoor setting. A summary of these results is provided in section 4.

Figure 3: WPI Fountain

Our second walking speed observation was conducted inside Higgins Labs in order to observe a situation that better represents an egress from within a building situation. For the indoor walking speed observations, we measured a distance of 25 feet in the center of the first floor hallway inside of Higgins Labs. We did not inform occupants we were timing their walking speed as they walked into the measured area. We took a total of ten measurements, the number of occupants walking into the area varying each time.

3.3.2 Observed Assembly Occupancy

Our group met to measure and record the time it took for occupants to reach the exit access inside Higgins Labs (HL) 116 once signaled to leave by the dismissal of class, as shown in figure 4. We measured the dimensions of all aspects of HL 116, such as the length and width of the room, the aisle and aisle accessways, the tables, and the doorways. Using a handheld stopwatch, we began recording from inside the room once occupants were dismissed to leave the room, disregarding any occupants who did not immediately react to dismissal from the professor.

We stopped the watch once all participating occupants proceeded through the exit access A and B of HL 116, as shown in figure 4. We repeated this process 16 times.

While one group member recorded from inside HL 116 the time it took for all occupants to reach the exit access doors, the rest of the group measured and recorded the time it took for occupants to travel from HL 116 to the hallway exits. First, we measured the width and length of the hallway and lobby on the first floor and the widths of all doorways involved. Using a handheld stopwatch, we began recording once the first occupant entered the hallway from HL 116, and stopped once the last person leaving HL 116 reached either exit 1 or the modified exit 2. We disregarded any occupants who did not immediately react to dismissal from the professor inside HL 116. The group member inside the classroom signaled to the rest of the group whom the last exiting occupant was that met our egress criteria. We stopped the watch once this occupant reached either of the two exits and counted how many people exited from either exit. We repeated this process 16 times. A summary of the results is provided in Section 4.

Figure 4: Higgins Labs with Modified Exit 2

3.4 Floor Plan Calculations

As a way to predict occupant travel time, calculation methods have been developed by fire protection engineers. We decided to follow the calculations published by the Society of Fire Protection Engineers (SFPE) to create a reproducible result and calculate a walking speed.[8] Based off of the models developed by SFPE, the three characteristics that are most important in occupant crowd movement throughout egress are speed, density, and flow. We did not include these factors in those that are addressed by NFPA 101. Each characteristic is defined as follows:

- *Density*- the number of occupants per unit area
- *Speed*- the time rate of motion of the occupants
- *Flow*- the rate at which occupants pass a particular point per unit of time

These characteristics relate to each other in the equation:

$$\text{Flow} = \text{Speed} \times \text{Density} \times \text{Width}$$

The SFPE model requires an understanding of the relationship between occupant motion and the features of the physical building, mainly the occupiable area. The density of a crowd movement significantly impacts the time required for all occupants to reach a point of safety.

3.4.1 Calculated Travel Time of Higgins Labs 116

Using HL 116, a timed egress calculation was performed to determine the time required for occupants to exit the lecture hall. Following the steps of SFPE egress calculation model, beginning with the aisles where the occupants are seated, the density was determined by dividing the number of occupants in each row by the net floor area of the aisle. The density directly determines the speed at which occupants can travel through the egress route. Using the SFPE model, the speed is calculated from the density by the following equation:

$$S=k-akD$$

where: S = Speed along the line of travel

D = Density (occupants/unit area)

k = Constant, as shown in Table 7 below, where $k = k1$

a = 2.86 when calculating speed in ft/min and density in persons/square ft.

The "k" value represents the correlation factor between the exit route elements, shown in Table 4,[8] and the egress calculation.

Table 4: Egress Calculation Correlation Constants

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

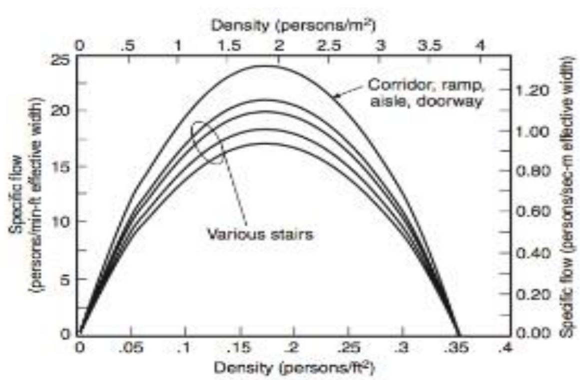
Note: 1 in. = 25.4 mm.

Next, it is determined how much the aisle width impedes the free flow of occupants through the aisle. The specific flow is a measurement of occupants passing a particular point in the egress path per unit of time and effective width. Specific flow is calculated by the following equation:

$$Fs=(1-aD)kD$$

Specific flow follows a parabolic relationship with the density of occupants. As shown in Figure 6,[8] the maximum specific flow occurs when the density is roughly 0.175 person/square ft.

Figure 5: Specific Flow as a Function of Density



Continuing to follow the SFPE egress calculation model, the next step is to determine the calculated flow rate Fc of the occupants through the aisle. The product of the specific flow and the effective width produce the calculated flow in units of persons/min.

$$F_c = F_s W_e$$

where: Fc= calculated flow

Fs= specific flow

We= effective width

Finally, time for passage, Tp, determines the time for all the occupants to pass through the aisle. This is found by the following equation:

$$T_c = P/F_c$$

where: P=population in persons

Once out of the aisle, the occupants move into aisle accessway. The flow of occupants through the aisle, and ultimately through the aisle accessway to the exit access door, is governed by the lowest specific flow along the entire path. For the lecture hall, the specific flow varies from the aisle to the aisle accessway. In this situation, the specific flow of the aisle was faster than that of the aisle accessway. Since the flow of occupants was governed by the aisle accessway, the specific flow rate of the occupants must also be calculated using the governing flow rate of the aisle accessway at the time the flows converge in the aisle accessway.

As occupants began filing out of the aisle and into the aisle accessway, crowding occurred at each transition point. The merging flows created congestion and caused a queue for the remaining occupants in the aisle. The SFPE model accounts for a queue time by giving precedence to those farthest from the exit access door. At the time of egress, occupants in aisle 7 of the lecture hall, as shown in Figure 6, are given the right of way through the aisle accessway. Using the time for passage and the distance from one aisle to the next, a queue time is calculated for each aisle. Once all the aisles have emptied, ending with the aisle closest to the exit access A, aisle 1, the time for the last occupant to travel from that row to the exit access A is determined by dividing the distance over the speed of travel. All together, the times are combined to determine a total travel time.

Figure 6: Modified Higgins Labs 116 and Adjacent Hallway

3.4.2 Calculated Travel Time of Higgins Labs Hallway to Exit 1

A timed egress calculation of the hallway adjacent to HL 116 follows similarly to the timed egress model of the lecture hall. Moving through the exit access, all the occupants pass through exits. Due to the conditions inside the lecture hall during egress, the specific flow rate through the exit access door from within the lecture hall governs the flow of occupants in the hallway.

Using the specific flow through the exit accessway door and the corresponding effective width, the calculated flow was determined. From this information, the time of passage through the exit access door was obtained. The time for the last occupant to travel from the exit access door to the exit was determined by dividing the length of travel by the occupant speed. Adding these two times provides the total time needed to egress the hallway.

3.4.3 Limitations of the Hand Calculations

For the purpose of simplifying the calculation, Higgins Labs 116 and the adjacent hallway, was reconfigured into a single level with only aisle accessway I, exit access A, and exit 1. The style of stairs in the lecture hall are difficult to account for in the SFPE calculation because the height and tread of the stairs in HL 116 do not correlate with the values given by SFPE as shown in Table 4. Using a single level lecture hall provides the ability to model the travel time with the SFPE model without the need to assume a "k" value. With this reconfiguration "k" corresponds to a corridor, aisle, ramp, or doorway as shown in Table 4. A modified version of HL 116 and the adjacent hallway, including only exit access A and exit 1, causes all occupants to travel through aisle access way I, exit access A, and exit 1 simplifying the calculation process. This simplification eliminates the need for numerous assumptions as to the route choice of the occupants.

3.5 Application of Pathfinder

Due to the complexity of human behavior, accurate analysis of travel time in real world situations is difficult to predict using simple models. Our group chose to use the egress simulation program Pathfinder, created by Thunderhead Engineering, to predict the travel time of occupants within fire situations.

3.5.1 Description of Pathfinder
3.5.2 Modeled Higgins Labs 116 in Pathfinder
3.5.3 Usefulness of Pathfinder
3.5.4 Modeled Higgins Labs First Floor in Pathfinder
3.5.5 Applied Relevant NFPA 101 Dimensional Limitations in Pathfinder
3.5.6 Simulated Scenarios of Higgins Labs in Pathfinder
3.5.7 Limitations of Pathfinder
3.5.8 Calculated Queue Time

3.5.1 Description of Pathfinder

Pathfinder is an egress simulation program developed by Thunderhead Engineering. It is designed to help provide simulations for analysis of how occupants travel through a building. There are two different types of occupant behavior settings that can be used by the 2015 version of Pathfinder as described:

- *Steering mode*– Provides for movement of occupants by considering collision detection and options to adjust flow rate limitations.
- *SFPE mode*– Uses similar variables from the SFPE handbook[8] but lacks collision detection and looks unnatural.

We decided to use steering mode when calculating travel times because steering mode provides a more realistic reproduction of occupant movement compared to SFPE mode. We also found SFPE mode to be unrepresentative of our observations in regards to occupant movement. The steering behavior mode presented simulations similar to our observations on occupant movement and their travel paths with other occupants around them. However, steering mode does not produce any type of queue time data in Pathfinder. Therefore, for the sole purpose of acquiring queue time data in our simulations, additional simulations were performed using SFPE mode in which only data relevant to the queue times was used.

3.5.2 Modeled Higgins Labs 116 in Pathfinder

In order to calculate an travel time, we needed to create a model of HL 116 as an input file for Pathfinder. We measured the dimensions inside HL 116 and the surrounding lobby the outside. The measurements were converted into meters, as that is the unit used in Pathfinder.

To compensate for the chairs in the classroom, we measured the width of the aisle between each table and subtracted 19 inches, adhering to NFPA 101. Doing so accounts for the space between the tables taken up by the seats. Aside from the first two tables, the distance from the end of the table to the wall alternates every other row roughly 3’ to 3’10” in distance as shown in Figure 6. In addition, the area of the chairs and small tables in the adjacent hallway leading to the exits was calculated and implemented so as not to differ from the true walking space occupants have to walk whilst leaving HL 116 as shown in Figure 6.

3.5.3 Usefulness of Pathfinder

As previously stated, the complexity of human behavior is difficult to predict using the SFPE models. This is due to the use of linear equations in the calculation.[8] For this reason our group chose to use Pathfinder to calculate the travel times of occupants in fire situations.

3.5.4 Modeled Higgins Labs First Floor in Pathfinder

To create the first floor of Higgins Labs in Pathfinder, our group obtained the Higgins Labs first floor plan (Figure 7) from WPI and uploaded it to AutoCAD. Once drawn in AutoCAD to scale, we were able to properly transfer the first floor into Pathfinder as shown in Figure 8. Creating this model was a time consuming process.

Figure 7: Higgins Labs First Floor Plans

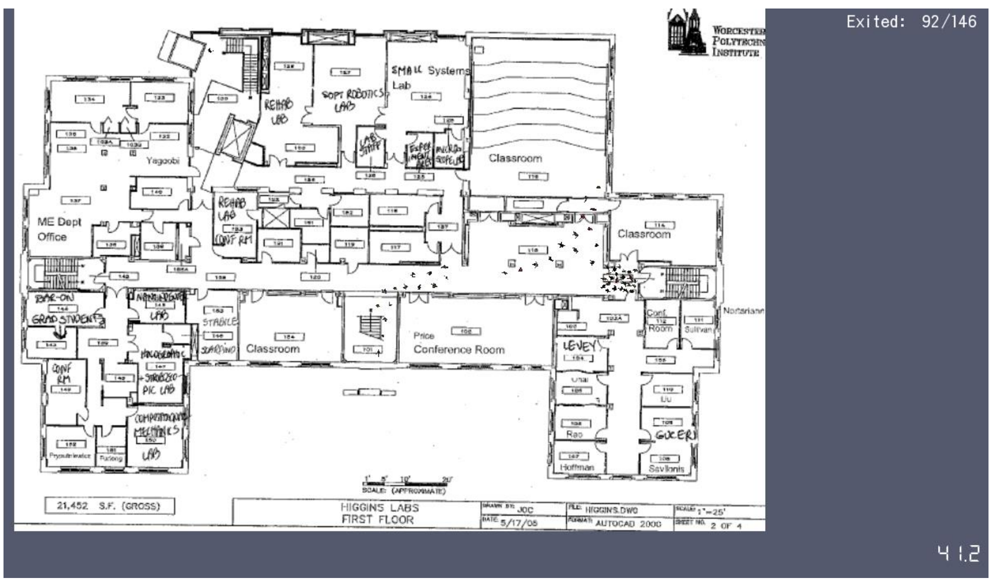


Figure 8: Higgins Labs First Floor in Pathfinder

3.5.5 Applied Relevant NFPA 101 Dimensional Limitations in Pathfinder

Using Pathfinder, our group established a maximum travel time for occupants to leave Higgins Labs First Floor based on the dimensional limitations of NFPA 101. We recreated the first floor of Higgins Labs within the dimensional limitations of NFPA for assembly and business occupancies. These limitations are displayed in Table 5 below. Each factor considered for testing was individually incorporated into the current layout of Higgins Labs, as explained in the next section, 3.5.6.

Table 5: Limiting Dimensions of Means of Egress Features

	Assembly Occupancy	Business Occupancy	Storage Occupancy
Travel Distance to Exit	Maximum of 200ft	Maximum of 200ft	
Common Path of Travel	Maximum of 75ft	Maximum of 100ft	
Number of Exits	Minimum of 3 between 500-1000 occupants	Minimum of 1 for under 100 occupants	
Door Widths	Minimum of 32 inches	Minimum of 32 inches	Minimum of 32 inches
Hallway Widths	Minimum of 44 inches	Minimum of 44 inches	
Aisle Width	Minimum of 36 inches		
Occupant Load	-Maximum based on number of seats for fixed seating; -15 net ft2/person2 for less concentrated seating	100ft2/person2	500ft2/person2

3.5.6 Simulated Scenarios of Higgins Labs in Pathfinder

In order to fully demonstrate the effect each of the above factors addressed by NFPA 101 have on travel time, we decided to run a variety of sensitivity tests isolating each factor and comparing it to the current layout of the entire Higgins Labs first floor. We also decided to create a model and run a simulation where all relevant dimensional limitations were involved in order to find the maximum time needed to reach the exits. Before running each scenario in Pathfinder, our group defined each dimensional limitation for the factor within the specific occupancy type and recreated the layout to accommodate each factor. We applied the limitations of an assembly occupancy in all of our models except for the offices areas in which we applied business occupancy limitations. These specifications are stated in Table 5 above.

The scenarios were as follows:

- Higgins First Floor
  - Current Higgins Labs First Floor Plan
  - Scenario A: Maximum Common Path of Travel
  - Scenario B: Minimum Hallway Width
  - Scenario C: Minimum Door Width
  - Scenario D: Minimum Number of Exits
  - Scenario E: Maximum Travel Distance to Exit
  - Scenario F: Maximum Occupant Load
  - Scenario G: All Relevant NFPA 101 Dimensional Limitations
  - Queue Time Simulation

3.5.7 Limitations of Pathfinder

Pathfinder is a very useful tool but has a few limitations that we had to work around. The first limitation was the inability to set a pre-evacuation time for occupants. Depending on the fire emergency situation of where the fire may be, occupants may feel less urgent to egress out of a building and might choose to grab their belongings or finish up whatever task they were doing. Pathfinder doesn't account for this as occupants begin egressing as quickly as possible once the simulation begins. Route choice is also a limitation of Pathfinder and is partially addressed in the program. Pathfinder allows for us to choose which exit accesses and exits we want each specific occupant to use in the egress simulation but doesn't allow us to physically draw the exact path we want an occupant to take. Due to our observations and research of occupant movement patterns, we decided to trust Pathfinder's algorithm on occupants travel choice as opposed to choosing the exits we wanted the occupants to use.

3.5.8 Calculated Queue Time

After determined the travel time for each scenario, the group chose to analyze queue times of different exits as displayed and explained in section 4 and 5 respectively. Using the data files generated by Pathfinder, the flow rate and number of occupants in different queues were compared. Using this data we were able to establish queue times for specific areas of interest.

4. Results

The results collected from the literature search, walking speed observations, and walking speed of floor plan calculations were analyzed to determine a walking speed for all Pathfinder simulations. Furthermore, the results collected from the Pathfinder simulations were analyzed for the affect each factor has on travel time and to determine a total travel time for Higgins Labs. Also the results of the Pathfinder simulations were used to calculate the queue time for different doorways as described below. This section states all numerical and graphical results. The analysis and discussion relevant to these results is provided in section 5.

Our results are broken up into the following order:

- 4.1 Literature Search Results
- 4.2 Observations
  - 4.2.1 Walking Speed-Fountain
  - 4.2.2 Walking Speed-Higgins Labs
  - 4.2.3 Assembly Occupancy
- 4.3 Floor Plan Calculations
- 4.4 Application of Pathfinder
  - 4.4.1 Creating Model of Higgins Labs 116
  - 4.4.2 Pathfinder Scenarios
    - 4.4.2.1 Current Higgins Labs First Floor
    - 4.4.2.2 Scenario A: Maximum Travel Distance to Exit
    - 4.4.2.3 Scenario B: Maximum Common Path of Travel
    - 4.4.2.4 Scenario C: Minimum Number of Exits
    - 4.4.2.5 Scenario D: Minimum Door Width
    - 4.4.2.6 Scenario E: Minimum Hallway Width
    - 4.4.2.7 Scenario F: Maximum Occupant Load
    - 4.4.2.8 Scenario G: All Relevant NFPA 101 Dimensional Limitations
  - 4.4.3 Queue Time Simulation

4.1 Literature Search Results

The Portland State University study resulted in an average walking speed of 4.85 ft/s (1.48 m/s) for younger pedestrians and 4.33 ft/s for older pedestrians.

The Japanese study we focused on published in the SFPE handbook found an average walking speed of 3.05 ft/s (0.93 m/s) for able-bodied adults walking with another person inside two shopping centers. These results were used as reference when deciding a walking speed determined in section 4.4.

4.2 Observations

The results for our observations at WPI as explained in section 3.3 are broken down into the following:

4.2.1 Walking Speed-Fountain
4.2.2 Walking Speed-Higgins Labs
4.2.3 Higgins Labs 116

4.2.1 Walking Speed-Fountain

We observed various people for a total of 30 minutes between classes, and found the average calculated walking speed to be 4.18ft/s (1.27 m/s). Our results can be found in Table 6 below and further discussion and analysis is provided in section 5.

Table 6: Walking Speed of WPI Students at the Fountain

Description	**Distance**	**Time**	**Speed (ft/s)**
Average male	50 ft	10.40 s	4.81
Athletic female, distracted	50 ft	11.50 s	4.35
Average female	29 ft	7.1 s	4.08
Group of 4	50 ft	14.49 s	3.45
Older male	50 ft	12.9 s	3.88
Average male, distracted	50 ft	26.30 s	1.9

Injured female on crutches	50 ft	14.82 s	3.37
Average female	29 ft	7.06 s	4.11
Male pushed in wheelchair	50 ft	8.87 s	5.64
Older female	50 ft	13.42 s	3.73
Group of 2	29 ft	6.33 s	4.58
Older female	29 ft	7.49 s	3.87
Group of 3, older	29 ft	6.91 s	4.2
Overweight male, distracted	29 ft	8.04 s	3.61
Older male	29 ft	5.86 s	4.95
Average male	50 ft	9.77 s	5.12
Older male and female	50 ft	10.97 s	4.56
Crowd - 10 people	46 ft	16.13 s	2.85
Group of 3	50 ft	15.31 s	3.27
Athletic female	50 ft	8.29 s	6.03
Older male	50 ft	10.48 s	4.77
Athletic female	50 ft	10.96 s	4.56
Older female	50 ft	12.10 s	4.13
Average male	50 ft	10.07 s	4.97
Group of 2	50 ft	22.00 s	2.27
Athletic female	50 ft	10.08 s	4.96
Female with arms full	50 ft	11.67 s	4.28
Overweight male	29 ft	8.50 s	3.41
Athletic female	50 ft	8.94 s	5.59
Average			4.18

4.2.2 Walking Speed-Higgins Labs

We found an average walking speed of 3.63 ft/s (1.12 m/s). The results are displayed in Table 7 below and further discussion and analysis can be found in section 5.

Table 7: Higgins Labs Walking Speeds

Number of People	Time (s)	Speed (ft/s)
1	6.1	4.10
1	6.68	3.74
1	6.56	3.81
1	6.21	4.03
1	7.07	3.54
3	8.38	2.98
3	8.0	3.13
2	6.93	3.61
1	5.82	4.30
2	8.24	3.03
Average		3.63

4.2.3 Higgins Labs 116

Table 8 below displays the results for occupants reaching the HL 116 exit access doors A and B and reaching exit 1 or the modified exit 2 from either exit access. This process was explained in section 3.3.2 with visual aid Figure 6. We found an average of 56 occupants inside HL 116 to reach the exit access in 120 seconds, and to reach the Higgins floor exits from HL 116’s exit access doors in 113 seconds. Further discussion and analysis is expanded on in section 5.

Table 8: Higgins Labs 116 Observations

Trial	Time for last occupant to reach exit access (s)	Time for last occupant to reach floor exit from exit access (s)	Number of Occupants
1	121	125	55
2	102	88	56
3	126	114	58
4	129	126	53
5	127	120	54
6	123	117	58
7	105	94	57
8	119	109	55
9	121	121	55
10	124	116	56
11	107	96	52
12	126	115	58
13	130	124	56
14	114	108	54
15	128	123	58
16	115	110	56
Average	120	113	56

4.3 Floor Plan Calculations

Using the speed of the occupants shown in Table 10 below and the distance of travel required, we calculated a total time of 72.8 seconds to egress from HL 116 to the adjacent hallway of the modified Higgins Lab model with the SFPE methods described in section 3.4.

The SFPE model for timed egress calculation gives a prediction on the time required for all occupants to escape. The dimensions for this calculation were chosen based off of the average observation that we conducted. For this egress calculation, the observed average of 56 occupants was accounted for with 8 occupants in each row. Following the SFPE model created for egress prediction the following values were calculated, with the final calculated value representing the total time required for all the occupants to escape. Discussion and analysis of these steps are provided in section 5.

Following the SFPE egress calculation model described in section 3, the following characteristic per aisle was calculated[8]:

Table 9: Density

Aisle	Density (occupants/ft^2)
1	0.1045
2	0.1045
3	0.112
4	0.1045
5	0.112
6	0.1045
7	0.112

Following the SFPE egress calculation model described in section 3, the following characteristic per aisle was calculated[8]:

Table 10: Speed

Aisle	Speed (ft/min)	(ft/s)	(m/s)
1	192.81075	3.2135125	0.996188875
2	192.81075	3.2135125	0.996188875
3	186.912	3.1152	0.965712
4	192.81075	3.2135125	0.996188875
5	186.912	3.1152	0.965712
6	192.81075	3.2135125	0.996188875
7	186.912	3.1152	0.965712

Following the SFPE egress calculation model described in section 3, the following characteristic per aisle was calculated[8]:

Table 11: Specific Flow

Aisle	Specific Flow Through the Aisle (occupants/min/ft^2)
1	20.14872338
2	20.14872338
3	20.934144
4	20.14872338
5	20.934144
6	20.14872338
7	20.934144

Following the SFPE egress calculation model described in section 3, the following characteristic per aisle was calculated[8]:

Table 12: Effective Width

Aisle	Effective Width of Aisle (ft)
1	2.5
2	2.3
3	2.3
4	2.3
5	2.3
6	2.3
7	2.3

Following the SFPE egress calculation model described in section 3, the following characteristic per aisle was calculated[8]:

Table 13: Initial Calculated Flow

Aisle	Initial Calculated Flow (occupants/min)
1	50.37180844
2	46.34206376
3	48.1485312
4	46.34206376
5	48.1485312
6	46.34206376
7	48.1485312

After exiting the row, occupants enter the aisle accessway. Similar calculations are completed for this component of the means of egress.

Table 14: Specific Flow of the Aisle Accessway

Aisle	Specific Flow of Aisle Accessway (occupants/min/ft^2)
1	14.72859896
2	13.55031104
3	14.07851789
4	13.55031104
5	14.07851789
6	13.55031104
7	14.07851789

Following the SFPE egress calculation model described in section 3, the following characteristic per aisle was calculated[8]:

Table 15: Effective Width of Aisle Accessway

Aisle	Effective Width of Aisle Accessway (ft)
1	3
2	3
3	3.83
4	3
5	3.83
6	3
7	3.83

Following the SFPE egress calculation model described in section 3, the following characteristic per aisle was calculated[8]:

Table 16: Calculated Flow of the Aisle Accessway

Aisle	Calculated Flow of Aisle Accessway (occupants/minute)
1	44.18579688
2	40.65093313
3	53.92072354
4	40.65093313
5	53.92072354
6	40.65093313
7	53.92072354
AVG	46.84296669

The flow of occupants out of the both the aisle and through the aisle accessway was governed by the flow of the aisle accessway, which was the slower of the two. The governing flow is used as the dominant flow for all calculations because the flow rate of the aisle can only be as fast as the aisle accessway.

Using the calculated flow shown in Table 16, the speed of occupants traveling in the aisle accessway before crowding was determined. The results are listed below in Table 17 and further discussion and analysis can be found in section 5.

Table 17: Speed of the Movement During Initial Aisle Accessway Travel

Aisle	Speed of Movement During Initial Aisle Accessway Travel (ft/min)
1	180.62
2	180.62
3	180.62
4	180.62
5	180.62
6	180.62
7	180.62

Table 18 defines the distance an occupant must travel from one aisle to the next. This data is combined with the speeds shown in Table 17 to determine the time to travel from aisle to aisle as listed in Table 19.

Table 18: Aisle to Aisle Travel Distance

Aisle	Aisle to Aisle Travel Distance (ft)
1	17
2	1.75
3	1.75
4	1.75
5	1.75
6	1.75
7	1.75

Table 19: Travel Time to Next Aisle

Aisle	Travel Time to Next Aisle (min)
1	0.094120252
2	0.00968885
3	0.00968885
4	0.00968885
5	0.00968885
6	0.00968885
7	0.00968885

As occupants begin entering the aisle accessway, crowding occurs at each aisle entry, slowing the flow of occupants. Table 20 defines the total number of occupants in the aisle accessway before crowding. It was assumed one occupant per aisle was in the aisle accessway before crowding occurred for a total of 7 occupants in the aisle accessway. Further discussion and analysis is provided in section 5.

Table 20: Calculation of Occupants in Aisle Accessway Before Crowding

Aisle	Calculated Flow of Aisle Accessway*Travel Time to Next Aisle
1	4.158778357
2	0.393860774
3	0.522429776
4	0.393860774
5	0.522429776
6	0.393860774
7	0.522429776
	2.74887165
	*2.74887165 refers to the number of people in the aisle accessway from row 2-7 before crowding occurs
	Assume 1 occupant from each aisle in aisle accessway before crowding begins

To account for the decrease in flow, the estimated impact of merger of aisle flow and aisle accessway flow is calculated in Table 21. Further discussion and analysis can be found in section 5.

Table 21: Estimated Impact of Merger of Aisle Flow and Aisle Accessway Flow

Aisle	Estimate Impact of Merger of Stairway Flow and Stairway Entry Flow on Exit Flow [Fs(out)] (occupants/min/ft^2)
1	31.51920177
2	28.99766563
3	34.02308491
4	28.99766563
5	34.02308491
6	28.99766563
7	34.02308491

Table 22 defines the remaining time needed to exit the aisle. Further discussion and analysis is expanded on in section 5.

Table 22: Time to Exit Aisle

Aisle	Time to Exit Aisle (min)
1	0.138966621
2	0.151050675
3	0.145383459
4	0.151050675
5	0.145383459
6	0.151050675
7	0.145383459

The aisle accessway is not capable of containing all the occupants as they restricts occupant flow and thus a point is reached where flow stops due to the number of occupants already in the aisle accessway. Therefore some occupants will have to wait in the aisle resulting in a queue. The SFPE egress calculation model gives the right of way for occupants farthest from the door. In this example, the queue is a combination of the time needed for the furthest aisle to empty and the last occupant from that aisle to pass the next aisle closest to the exit access door.

Using the governing flow along the egress route, the calculation model predicts the time required for an occupant to travel from one row to the next is 1 second. Adding 1 second to the time required to empty the row gives the total time needed for a row to empty and all occupants from that row to clear the path of occupants in the next row. Once the row closest to the exit access door is empty, the last occupant from that row requires a certain amount of time to reach the exit access door. Using the flow and the distance between the first row and the exit access door, the time required to travel is calculated as 5 seconds.

Adding up all of these results gives the total time required for all 56 occupants to leave the HL 116 lecture hall. From the instant the first occupant begins moving toward the exit access door until the last occupant passes through the exit access door, the SFPE model predicts a time 72.8 seconds required to escape.

The SFPE egress calculation model was also used to determine the time required for the occupants to make their way through the hallway adjacent to HL 116 and move into exit 1, illustrated in Figure 6. The governing flow occurs in the aisle accessway within the classroom. This causes the occupants to flow out of the classroom and through the hallway at the same rate as they pass through the aisle accessway. To account for this, the average specific flow rate and average effective width of the aisle accessway were used to calculate the flow rate of the egress route through the hallway adjacent to HL 116. It was calculated that 56 occupants pass through the exit access door at a rate of 46 persons/min. The total time required for all the occupants to pass through the exit access door and into the exit access is 72.8 seconds. Finally, the last occupant requires time to travel from the exit access door to the exit door. Using the speed of the occupants and the distance of travel required, the SFPE egress model predicts a time of 82.7 seconds for all occupants to travel from the exit access through the hallway of the modified HL 116 to exit 1 as shown in Figure 6. Further discussion and analysis is provided in section 5.

4.4 Application of Pathfinder

Before beginning our sensitivity test, we had to determine a final average walking speed. After reviewing the results from our literature search, observations, and SPFE calculations, we ultimately decided to trust the walking speed calculated from the SFPE model. We have the most confidence in this value because we trust that the SFPE model provides the closest travel speed to that of an occupant in an egress situation opposed to the studies found in our literature search and observations, which were not fire situations. The final walking speed we decided on was 0.965 m/s. Further explanation of this process is explained in section 5.1.

4.4.1 Model of Higgins Labs 116

The hand calculations accounted for 8 people entering aisle accessway I from each aisle with an average walking speed of 0.965 m/s (190ft/min). We created a Pathfinder simulation that had equivalent parameters and variables as the floor plan calculations to compare with the results of the floor plan calculations. The comparison results are as followed:

Time taken for first person to move and last person to pass through exit access door:

Pathfinder – 71.8 seconds

Hand Calculation – 72.8 seconds

Time taken for the first person the move through the exit access door to the last person to exit adjacent hallway :

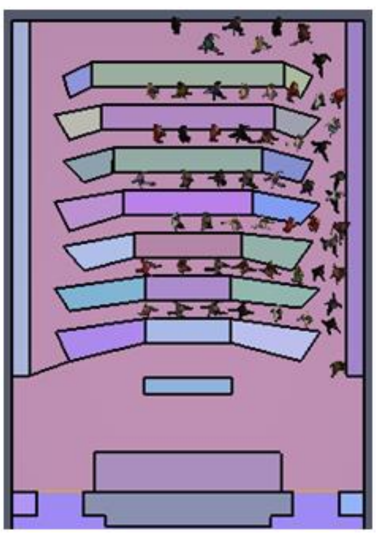
Pathfinder - 74.5 seconds

Hand Calculation- 82.7 seconds

ROOM/DOOR	FIRST IN (s)	LAST OUT (s)	TOTAL USE (pers)	FLOW AVG. (pers/s)
m->Hallway	8.4	82.9	56	
m->Exit 1	18.2	82.9	56	0.87
m->N/A	0.0	0.0	0	
m->EA A	8.4	71.8	56	0.88
m->HL 116	0.0	71.8	56	

Pathfinder proved to be 1 second faster than our hand calculations. Pathfinder simulations produce the same result for each simulation unless the occupant's location changes or there is a change within the model of the building, therefore the process wasn't repeated. HL 116 recreated in Pathfinder is shown in Figure 9 below. Further discussion and analysis is provided in section 5.

Figure 9: Pathfinder Higgins Labs 116 Simulation



4.4.2 Pathfinder Scenarios

Our results are displayed in an order based on our group's original list of what we consider to have the greatest to the least influence on travel time. Since "All Relevant NFPA 101 Dimensional Limitations" was a compilation of all factor of means of egress we initially considered for testing, we added it to the end of the pathfinder scenarios list. For each section, a minimum and maximum time to reach the exit is provided, which represents the time it took the first person and last person to reach the exit respectively. Also provided is the summary table outputted from Pathfinder and visual aids on the set up as well as during the simulation. These results summarize the application of Pathfinder methods described in section 3, and are further analyzed in section 5.

1. Current HL Floor Plan
2. Scenario A: Maximum Travel Distances to Exit
3. Scenario B: Maximum Common Path of Travel
4. Scenario C: Minimum Number of Exits
5. Scenario D: Minimum Door Width
6. Scenario E: Minimum Hallway Width
7. Scenario F: Maximum Occupant Load
8. Scenario F: All Relevant NFPA 101 Dimensional Limitations

4.4.2.1 Current Higgins Labs First Floor

This section provides the numerical and visual results for the Pathfinder simulation of the current Higgins Labs first floor. Further discussion and analysis is described in section 5.

Table 23: Current Higgins Labs First Floor

	Current Layout Min Time (s)	**Current Layout Max Time(s)**
Higgins First Floor	4.9	80.9

Figure 10: Current Higgins Labs Results Summary

```
Simulation:          FullHLfloor
Version:             2015.1.0520
Mode:                Steering
Total Occupants:     142
Exit Times (s):
  Min:               4.9
  Max:               80.9
```

Figure 11: Current Higgins Labs Initial Setup

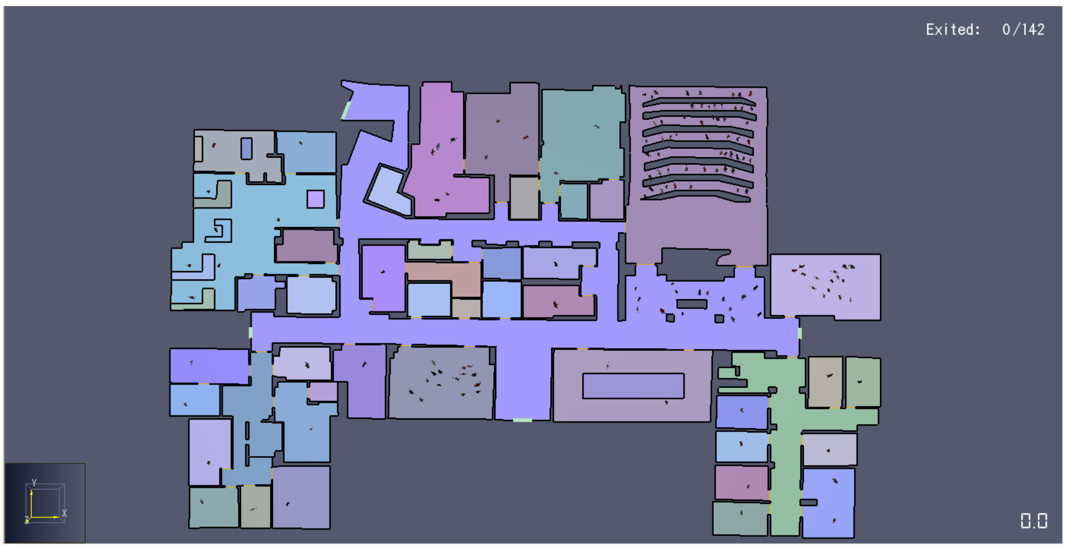
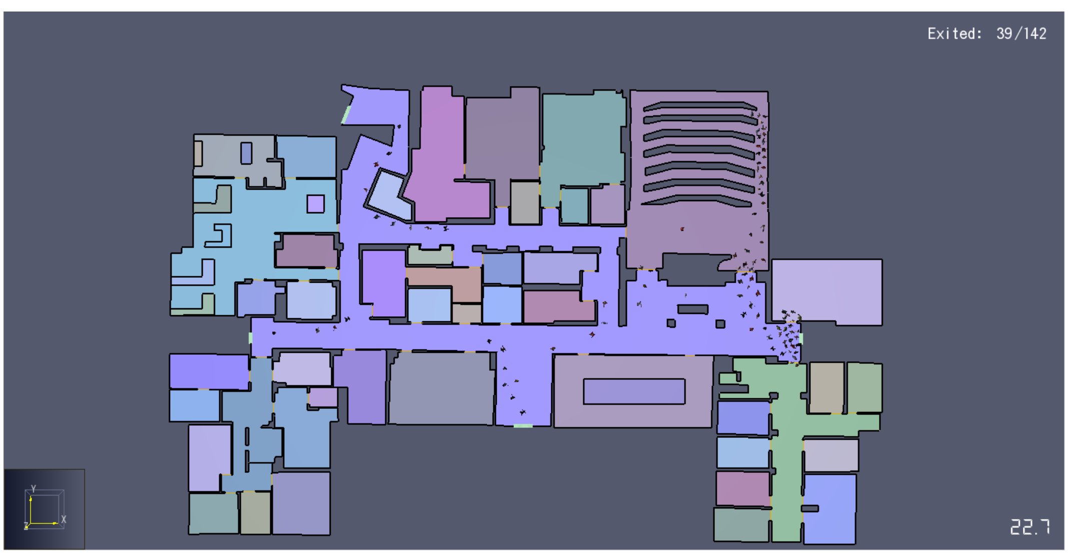


Figure 12: Current Higgins Labs Simulation



4.4.2.2 Scenario A: Maximum Travel Distance to Exit

This section provides the numerical and visual results for the Pathfinder simulation of the maximum travel distance to the exits. Further discussion and analysis is described in section 5.

Table 24: Travel Distance to Exit

	Current Layout Min Time (s)	**Current Layout Max Time(s)**	**NFPA 101 Standards and Limitations Min Time (s)**	**NFPA 101 Standards and Limitations Max Time (s)**
Higgins First Floor	4.9	80.9	31.2	113.7

Figure 13: Maximum Travel Distance to Exit Results Summary

```
Simulation:          higgins mtdte
Version:             2015.1.0520
Mode:                Steering
Total Occupants:     142
Exit Times (s):
  Min:               31.2
  Max:               113.7
```

Figure 14: Maximum Travel Distance to Exit Initial Setup

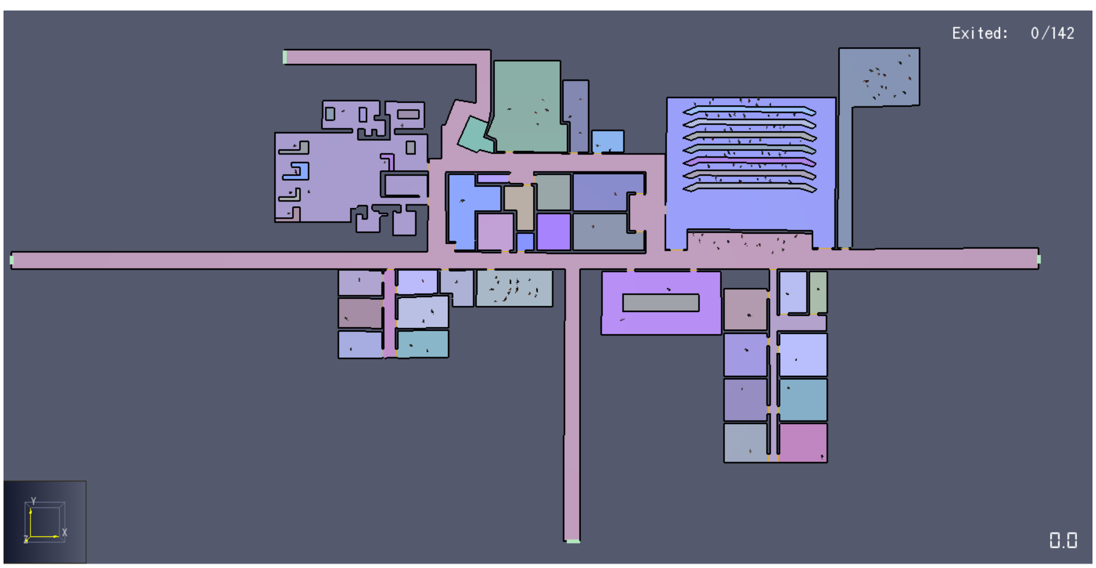
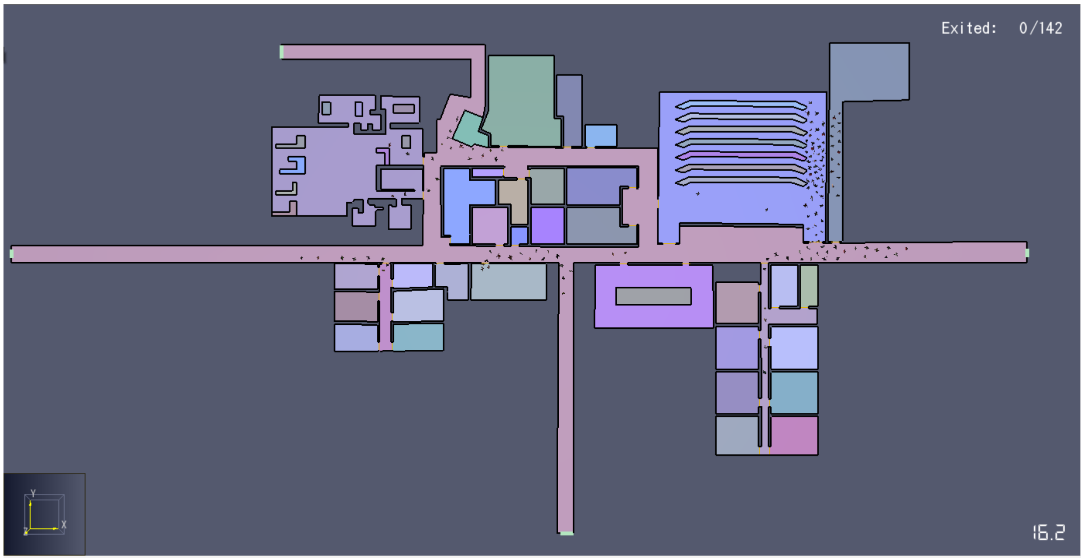


Figure 15: Maximum Travel Distance to Exit Simulation



4.4.2.3 Scenario B: Maximum Common Path of Travel

This section provides the numerical and visual results for the Pathfinder simulation of the maximum common path of travel. Further discussion and analysis is described in section 5.

Table 25: Maximum Common Path of Travel

	Current Layout Min Time (s)	**Current Layout Max Time(s)**	**NFPA 101 Standards and Limitations Min Time (s)**	**NFPA 101 Standards and Limitations Max Time (s)**
Higgins First Floor	4.9	80.9	4.5	78.1

Figure 16: Maximum Common Path of Travel Results Summary

Simulation:	MaxCommonPathOfTravelHL
Version:	2015.1.0520
Mode:	Steering
Total Occupants:	142
Exit Times (s):	
Min:	4.5
Max:	78.1

Figure 17: Maximum Common Path of Travel Initial Setup

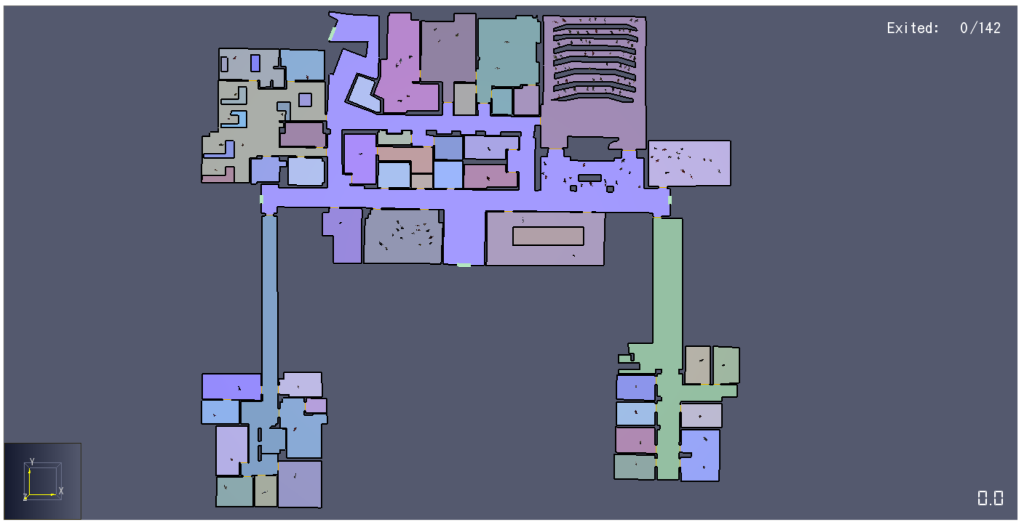
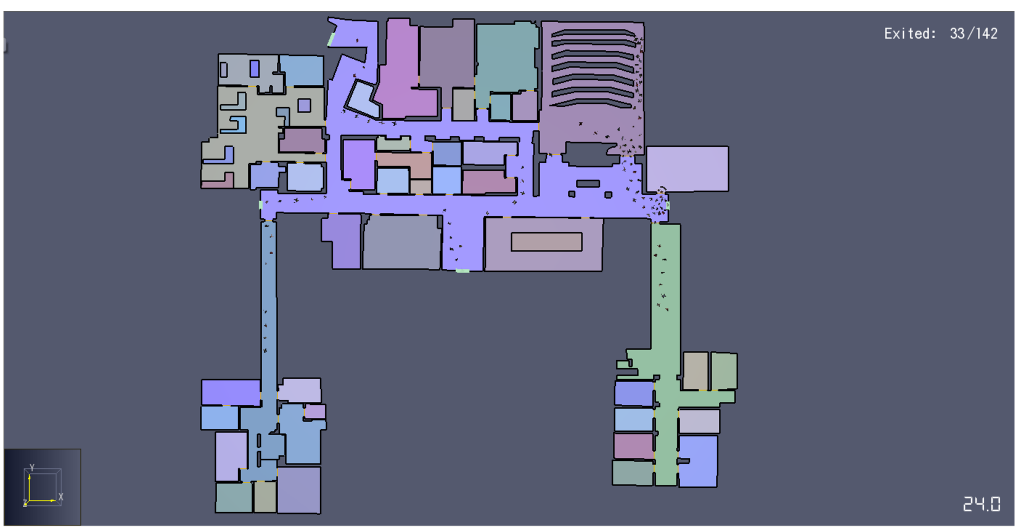


Figure 18: Maximum Common Path of Travel Simulation



4.4.2.4 Scenario C Minimum Number of Exits

This section provides the numerical and visual results for the Pathfinder simulation of the minimum number of exits. Further discussion and analysis is described in section 5.

Table 26: Minimum Number of Exits

	Current Layout Min Time (s)	Current Layout Max Time(s)	NFPA 101 Standards and Limitations Min Time (s)	NFPA 101 Standards and Limitations Max Time (s)
Higgins First Floor	4.9	80.9	5.1	103.1

Figure 19: Minimum Number of Exits Results Summary

```
Simulation:          MinimumExits
Version:             2015.1.0520
Mode:                Steering
Total Occupants:     142
Exit Times (s):
  Min:               5.1
  Max:               103.1
```

Figure 20: Minimum Number of Exits Initial Setup

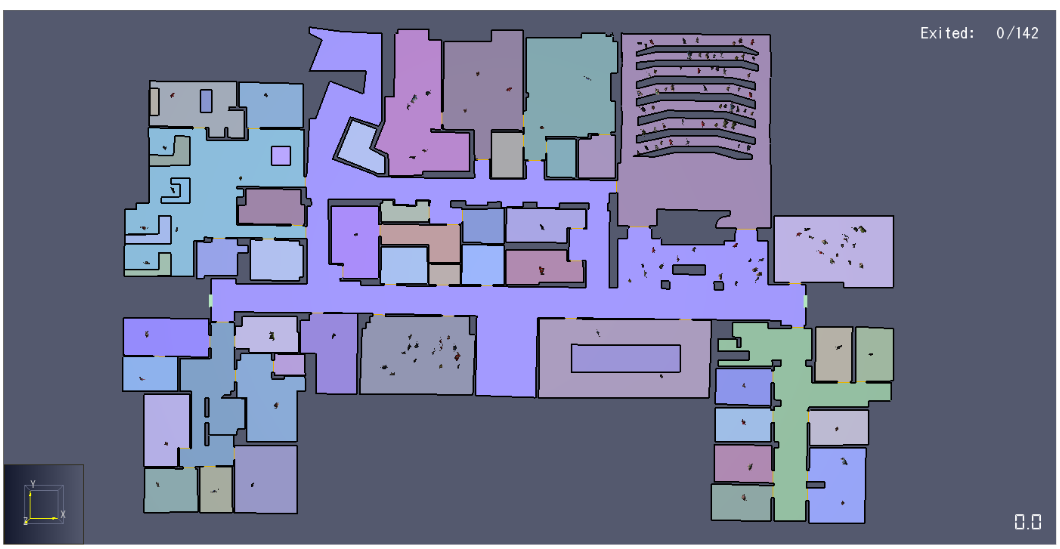
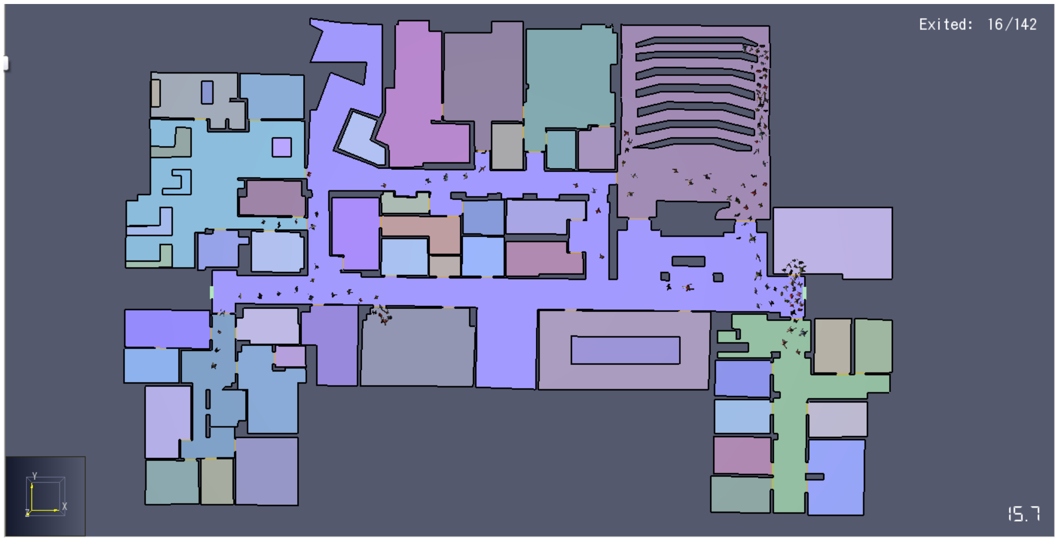


Figure 21: Minimum Number of Exits Simulation



4.4.2.5 Scenario D: Minimum Door Width

This section provides the numerical and visual results for the Pathfinder simulation of the minimum door width. Further discussion and analysis is described in section 5.

Table 27: Minimum Door Widths

	Current Layout Min Time (s)	**Current Layout Max Time(s)**	**NFPA 101 Standards and Limitations Min Time (s)**	**NFPA 101 Standards and Limitations Max Time (s)**
Higgins First Floor	4.9	80.9	6.1	84.1

Figure 22: Minimum Door Width Results Summary

Simulation:	MinimumDoorWidth
Version:	2015.1.0520
Mode:	Steering
Total Occupants:	142
Exit Times (s):	
Min:	6.1
Max:	84.1

Figure 23: Minimum Door Width Initial Setup

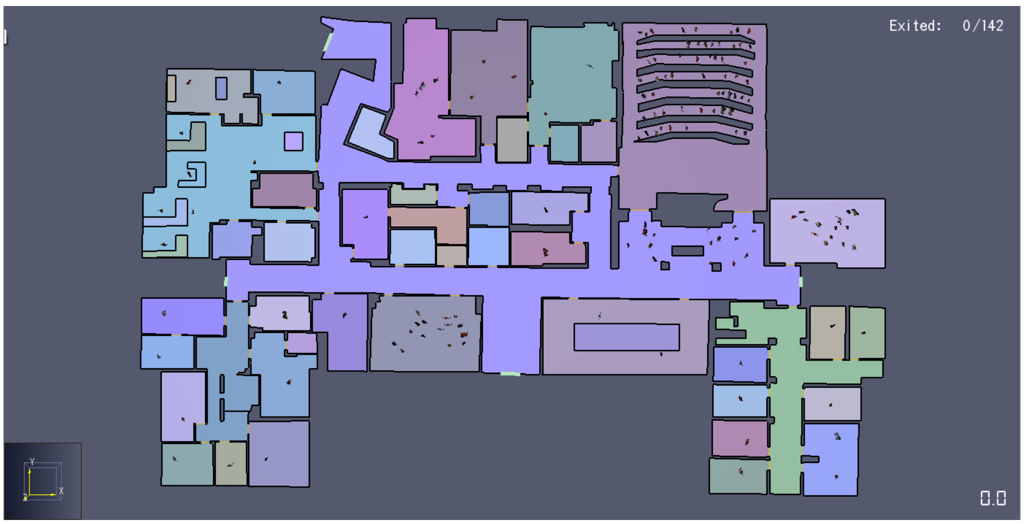
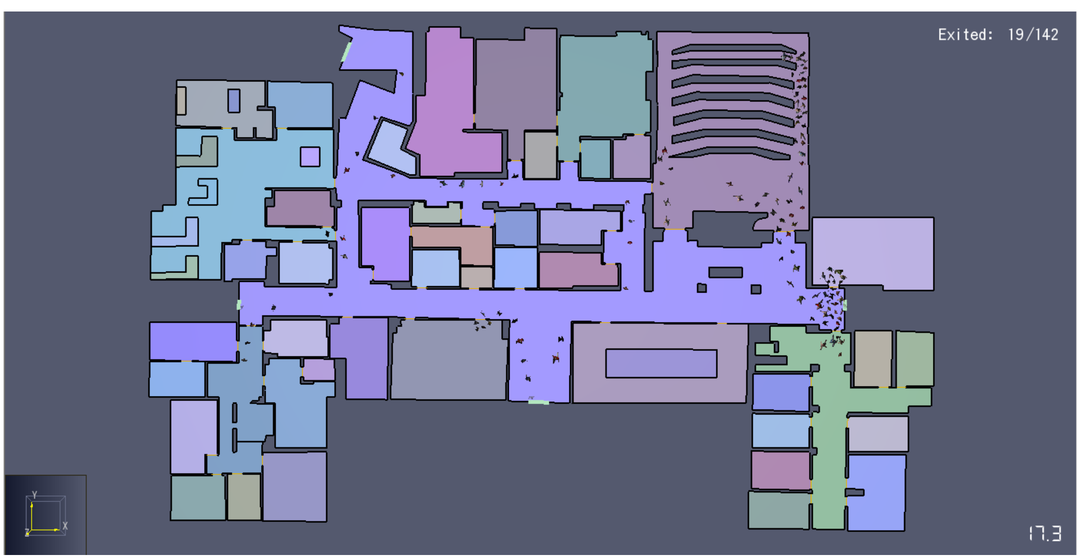


Figure 24: Minimum Door Width Simulation



4.4.2.6 Scenario E: Minimum Hallway Width

This section provides the numerical and visual results for the Pathfinder simulation of the minimum hallway width. Further discussion and analysis is described in section 5.

Table 28: Minimum Hallway Width

	Current Layout Min Time (s)	Current Layout Max Time(s)	NFPA 101 Standards and Limitations Min Time (s)	NFPA 101 Standards and Limitations Max Time (s)
Higgins First Floor	4.9	80.9	5.4	79.6

Figure 25: Minimum Hallway Width Results Summary

```
Simulation:          MinimumHallwayWidth
Version:             2015.1.0520
Mode:                Steering
Total Occupants:     142
Exit Times (s):
  Min:               5.4
  Max:               80.5
```

Figure 26: Minimum Hallway Width Initial Setup

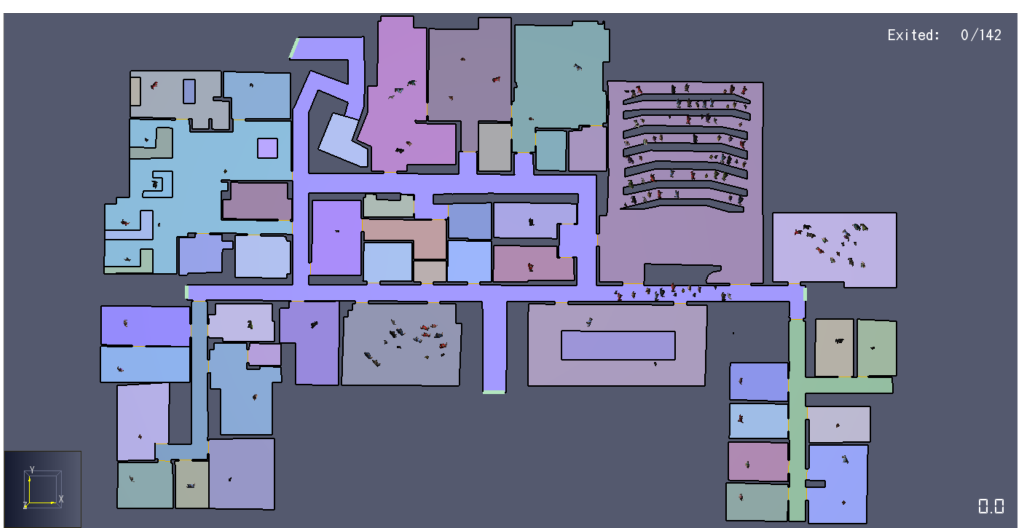
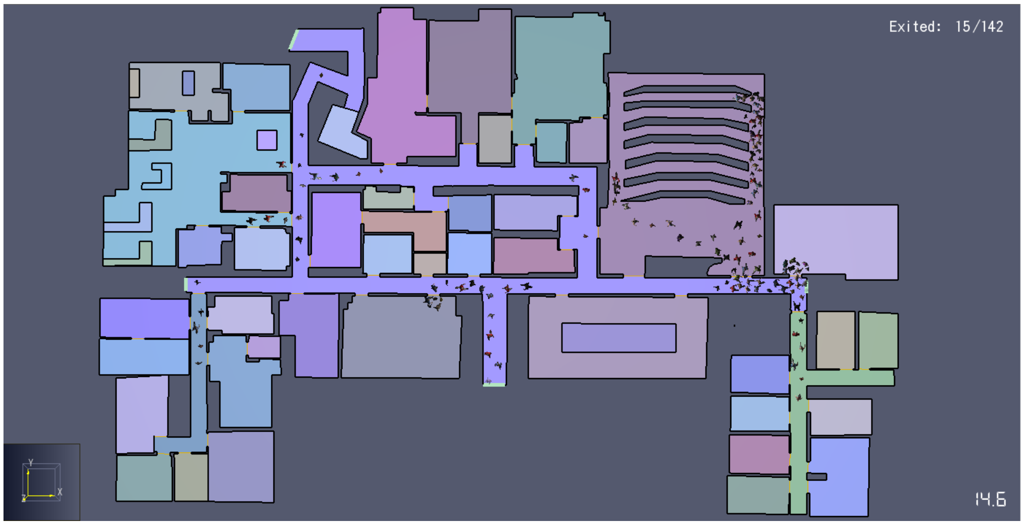


Figure 27: Minimum Hallway Width Simulation



4.4.2.7 Scenario F: Maximum Occupant Load

This section provides the numerical and visual results for the Pathfinder simulation of the maximum occupant load. Further discussion and analysis is described in section 5.

Table 29: Maximum Occupant Load

	Current Layout Min Time (s)	**Current Layout Max Time(s)**	**NFPA 101 Standards and Limitations Min Time (s)**	**NFPA 101 Standards and Limitations Max Time (s)**
Higgins First Floor	4.9	80.9	2.5	117.3

Figure 28: Maximum Occupant Load Results Summary

Simulation:	FullHLfloorMO
Version:	2015.1.0520
Mode:	Steering
Total Occupants:	366
Exit Times (s):	
Min:	2.5
Max:	117.3

Figure 29: Maximum Occupant Load Initial Setup

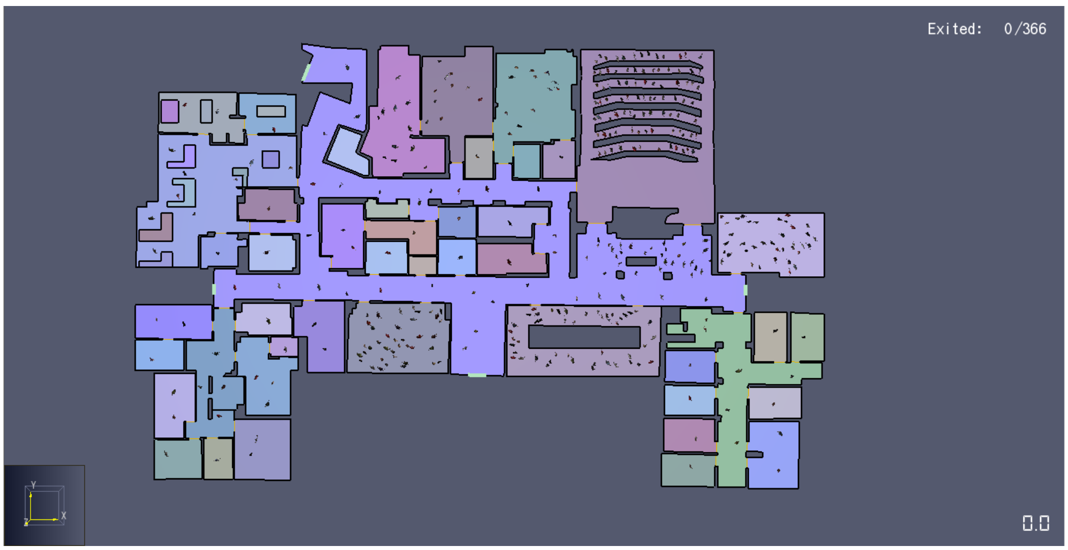
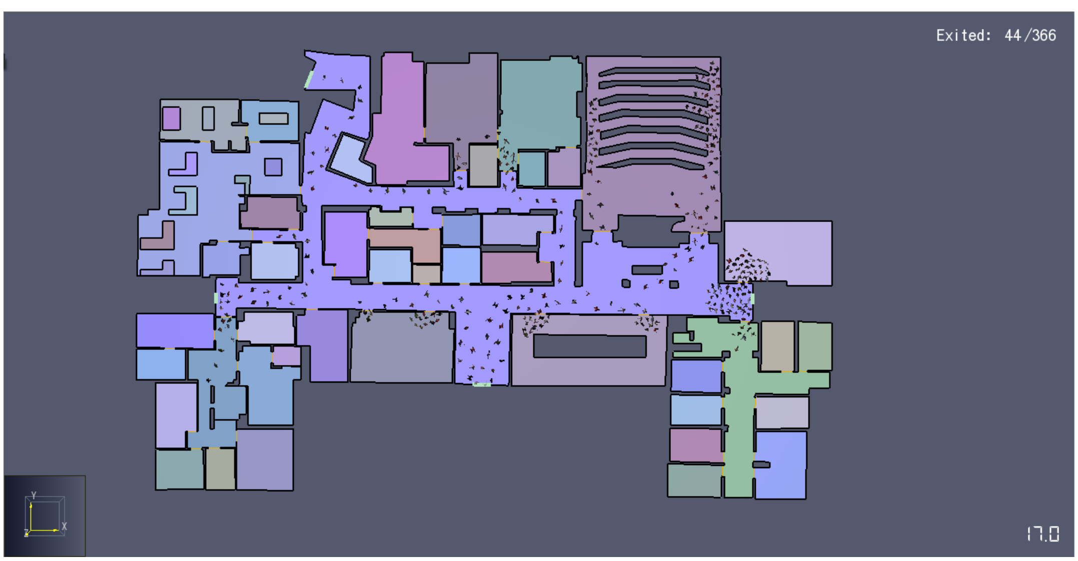


Figure 30: Maximum Occupant Load Simulation



4.4.2.8 Scenario G: All Relevant NFPA 101 Dimensional Limitations

This section provides the numerical and visual results for the Pathfinder simulation of all relevant NFPA 101 dimensional limitations. Further discussion and analysis is described in section 5.

Table 30: All Factors

	Current Layout Min Time (s)	**Current Layout Max Time(s)**	**NFPA 101 Standards and Limitations Min Time (s)**	**NFPA 101 Standards and Limitations Max Time (s)**
Higgins First Floor	4.9	80.9	3.7	500.7

All Relevant NFPA 101 Dimensional Limitations:

Figure 31: All Relevant NFPA 101 Dimensional Results Summary

```
Simulation:          higgins all factors
Version:             2015.1.0520
Mode:                Steering
Total Occupants:     794
Exit Times (s):
  Min:               3.7
  Max:               500.7
```

Figure 32: All Relevant NFPA 101 Dimensional Initial Setup

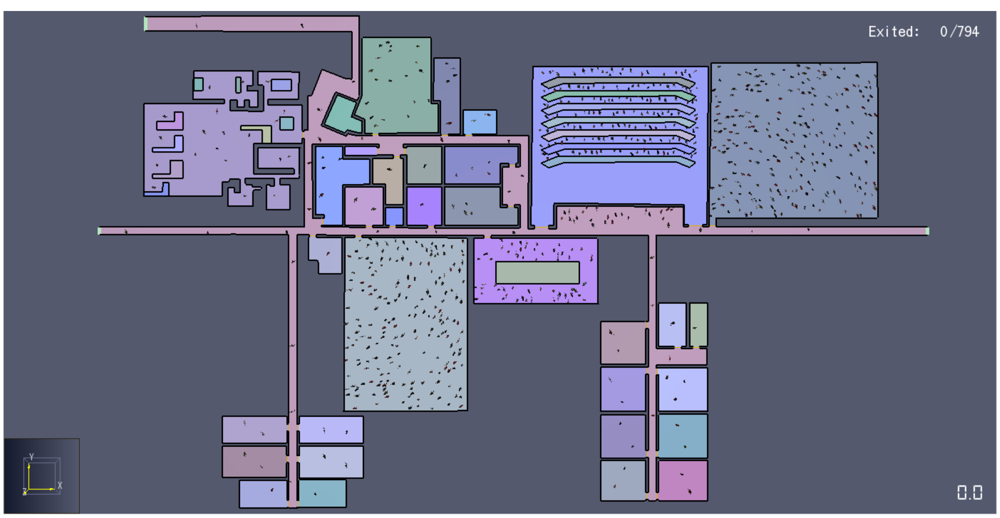
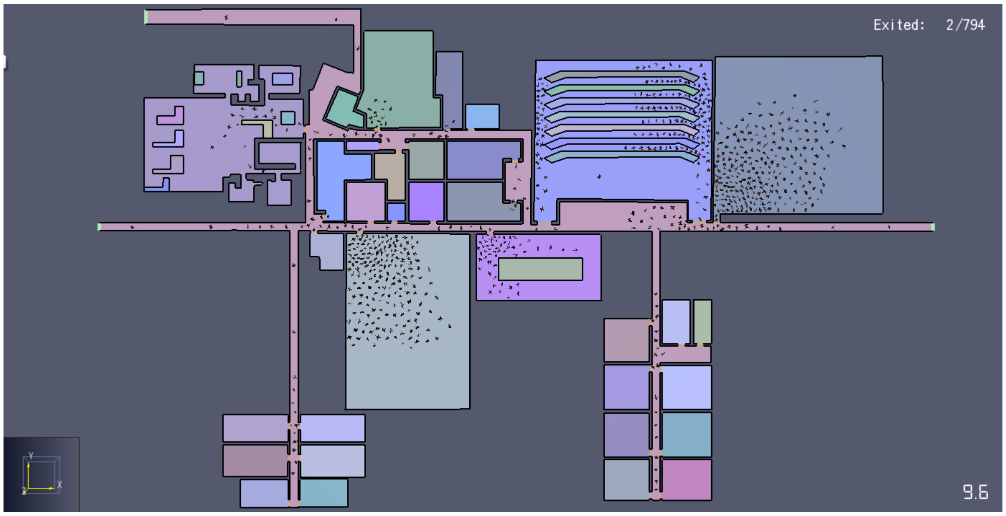


Figure 33: All Relevant NFPA 101 Dimensional Simulation



The results of all the scenarios are illustrated in Table 31 below.

Table 31: Pathfinder Sensitivity Tests Result Summary

Scenario	Maximum Time for Egress (s)
Current Higgins Labs First Floor Plan	80.9
A: Maximum Common Path of Travel	78.1
B: Minimum Hallway Width	80.5
C: Minimum Door Width	84.1
D: Minimum Number of Exits	103.1
E: Maximum Travel Distance to Exit	113.7
F: Maximum Occupant Load	117.3
G: All Relevant NFPA 101 Dimensional Limitations	500.7

4.4.3 Queue Time

This section provides the numerical and graphical results for the Pathfinder simulation of the queue times for various doorways of both the current Higgins Labs first floor and when all relevant NFPA 101 dimensional limitations are incorporated. Further discussion and analysis is described in section 5.

Figure 34 illustrates the flow rate through Higgins Labs 116 exit access A of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 34: Current Higgins Labs Exit Access A Flow Rate

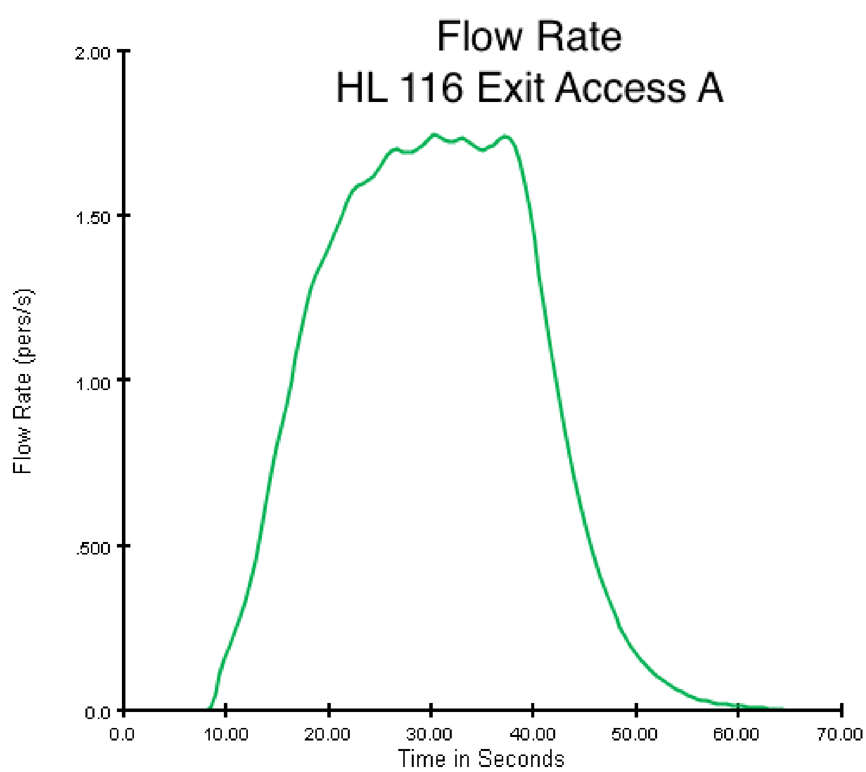


Figure 35 illustrates the correlation between the number of occupants in the queue and their respective queue time through the Higgins Labs 116 exit access A of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 35: Queue Time Current Higgins Labs Exit Access A

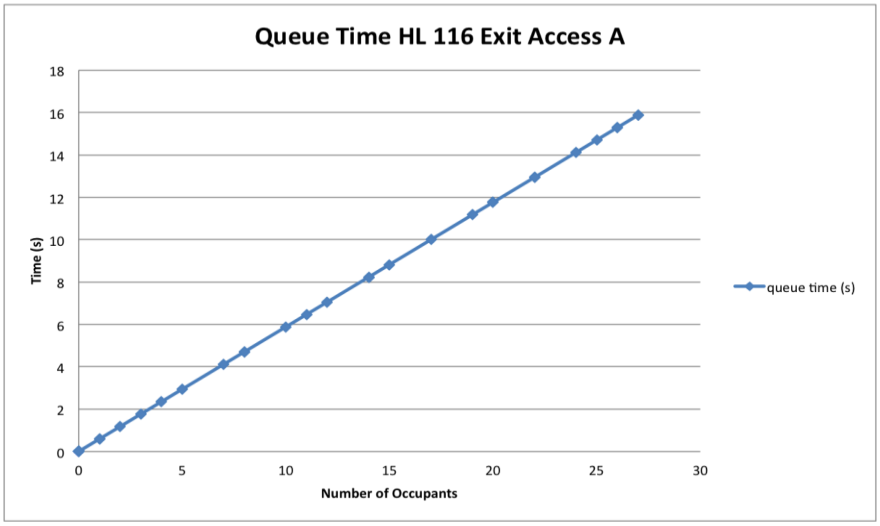


Figure 36 illustrates the instantaneous queue time relative to the total travel time of each occupant in the queue respectively, through the Higgins Labs 116 exit access A of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 36: Instantaneous Queue Time Current Higgins Labs 116 Exit Access A

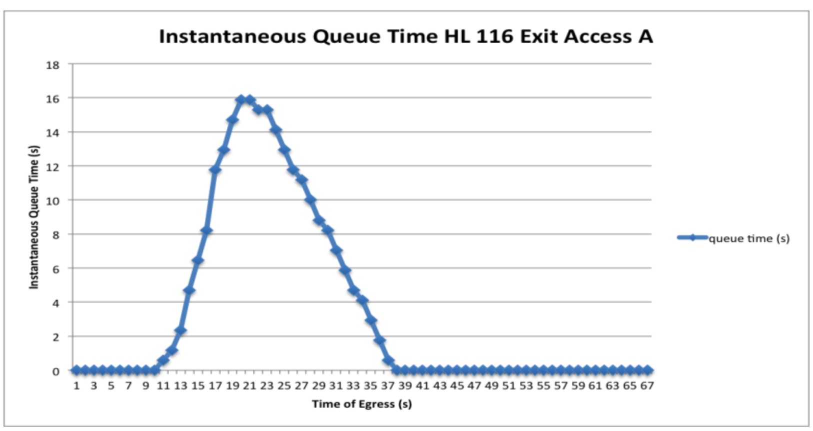


Figure 37 illustrates the flow rate through the exit access of HL 114 of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 37: Current Higgins Labs 114 Flow Rate

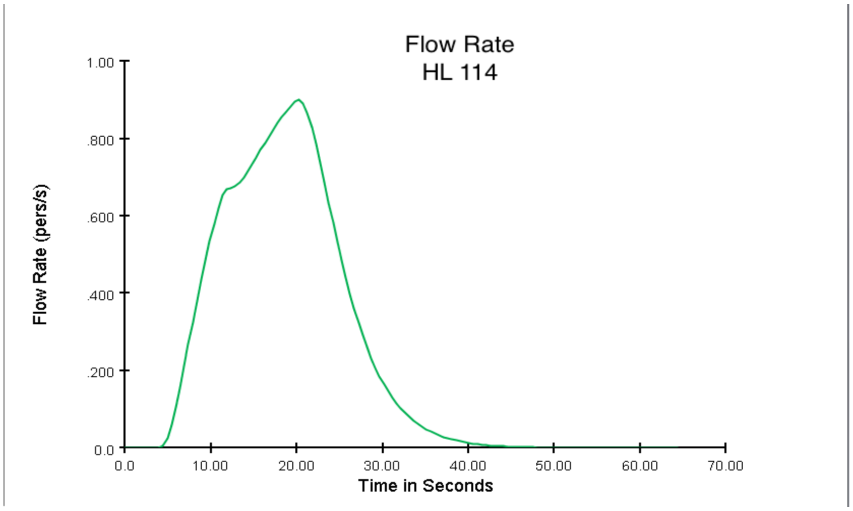


Figure 38 illustrates the correlation between the number of occupants in the queue and their respective queue time through the Higgins Labs 114 exit access of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 38: Queue Time Current Higgins Labs 114

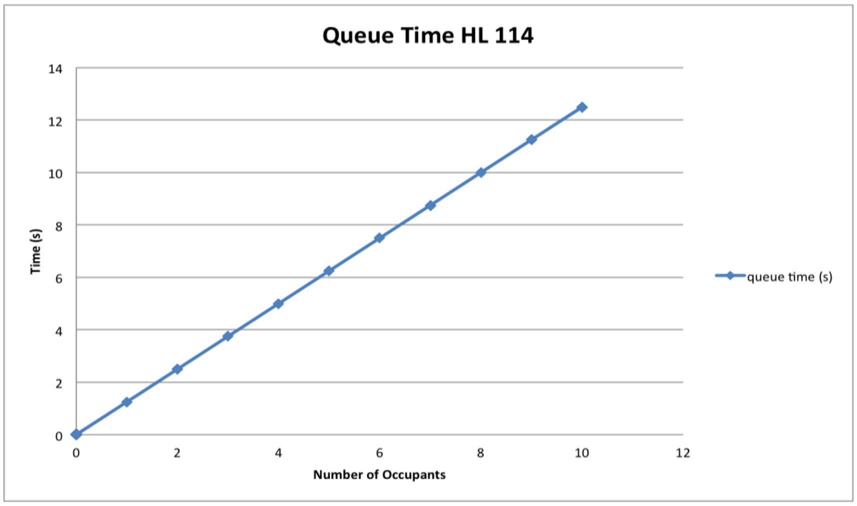


Figure 39 illustrates the instantaneous queue time relative to the total travel time of each occupant in the queue respectively, through the Higgins Labs 114 exit access of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 39: Instantaneous Queue Time Current Higgins Labs 114

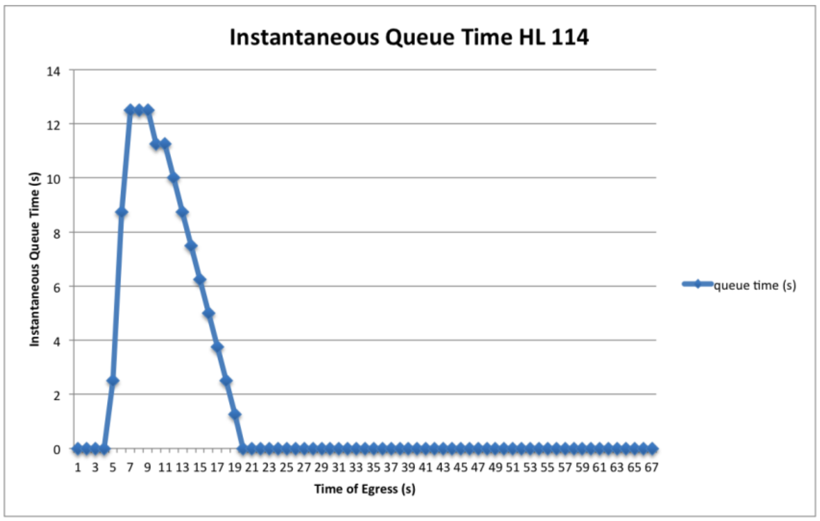


Figure 40 illustrates the flow rate through Exit 1 of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 40: Current Higgins Labs Exit 1 Flow Rate

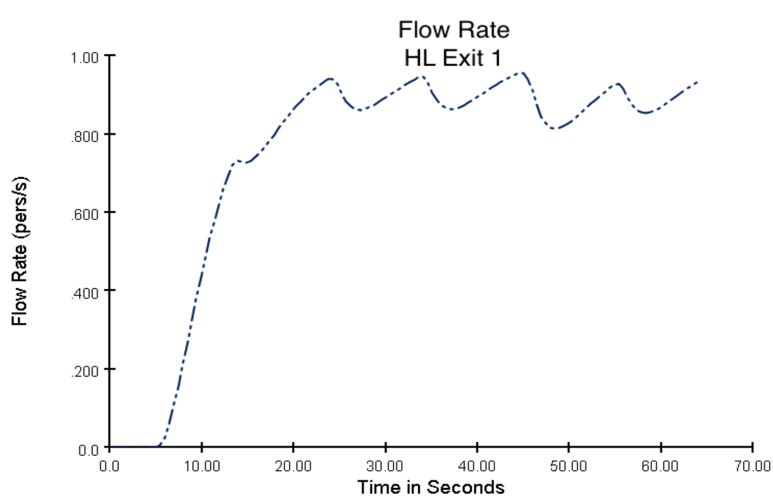


Figure 41 illustrates the correlation between the number of occupants in the queue and their respective queue time through Exit 1 of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 41: Queue Time Current Higgins Labs Exit 1

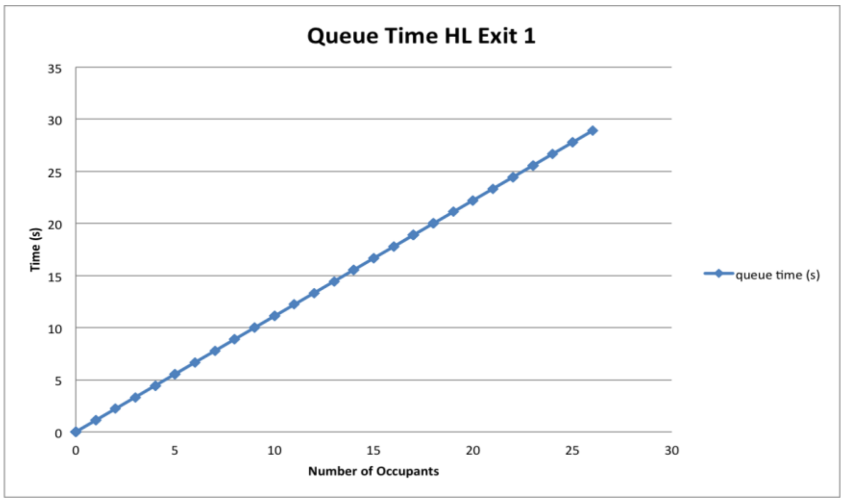


Figure 42 illustrates the instantaneous queue time relative to the total travel time of each occupant in the queue respectively, through the Exit 1 of the current Higgins Labs floor plan during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 42: Instantaneous Queue Time Current Higgins Labs Exit 1

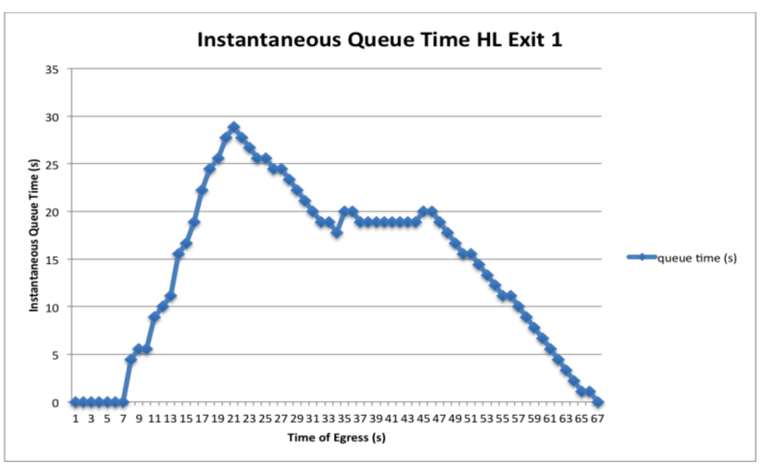


Figure 43 illustrates the flow rate through Higgins Labs 116 exit access A of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 43: All Relevant NFPA 101 Dimensional Limitations Higgins Labs Exit Access A Flow Rate

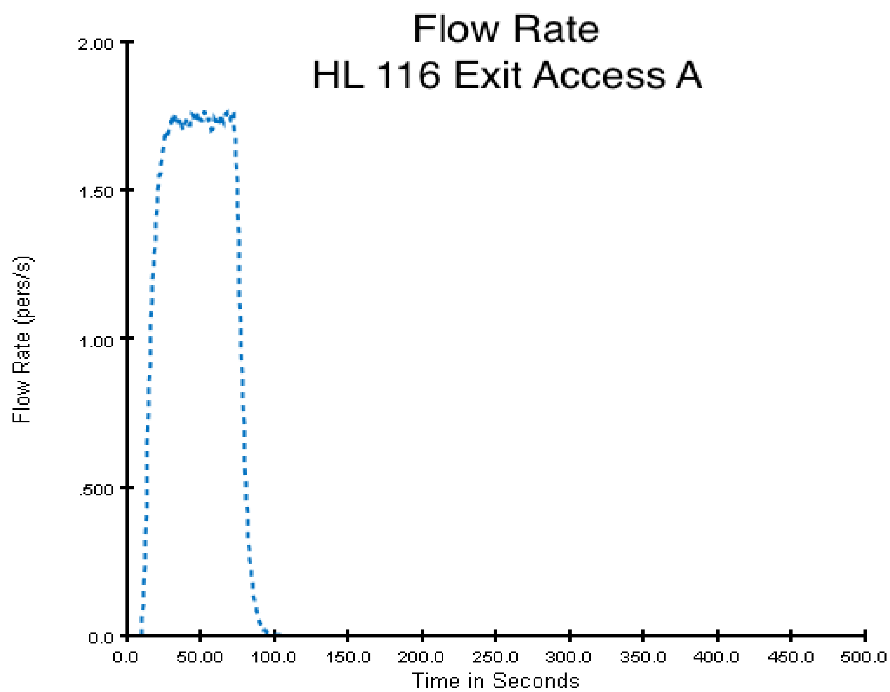


Figure 44 illustrates the correlation between the number of occupants in the queue and their respective queue time through Higgins Labs 116 exit access A of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 44: Queue Time All Relevant NFPA 101 Dimensional Limitations Higgins Labs 116 Exit Access A

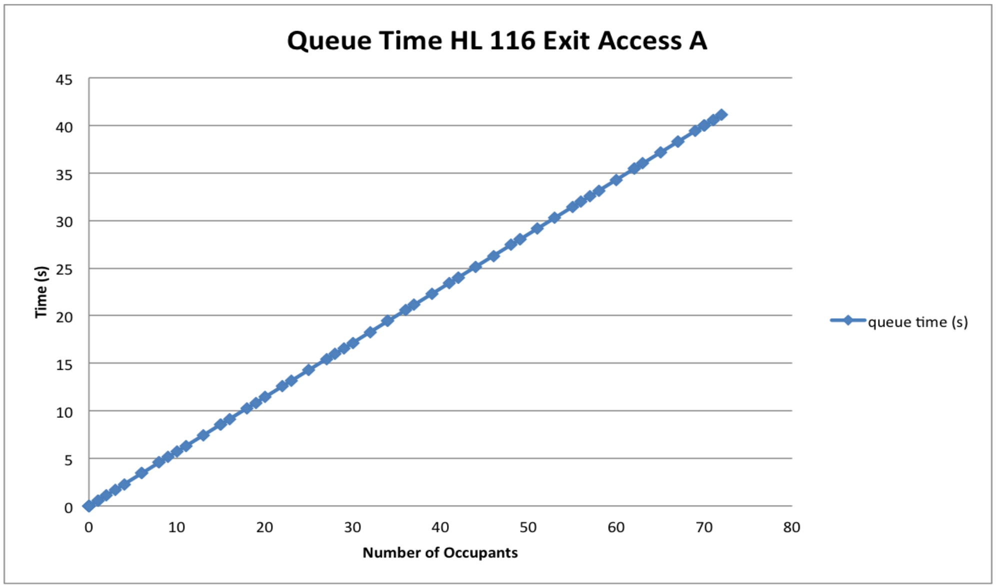


Figure 45 illustrates the instantaneous queue time relative to the total travel time of each occupant in the queue respectively, through exit access A of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 45: Instantaneous Queue Time All Relevant NFPA 101 Dimensional Limitations Higgins Labs 116 Exit Access A

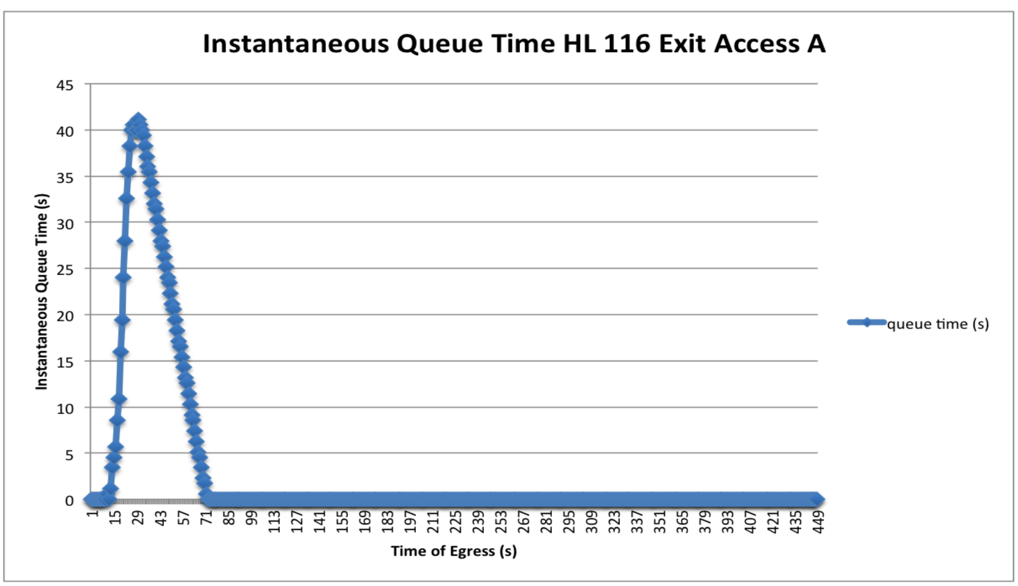


Figure 46 illustrates the flow rate through Higgins Labs 114 exit access of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 46: All Relevant NFPA 101 Dimensional Limitations Higgins Labs 114 Flow Rate

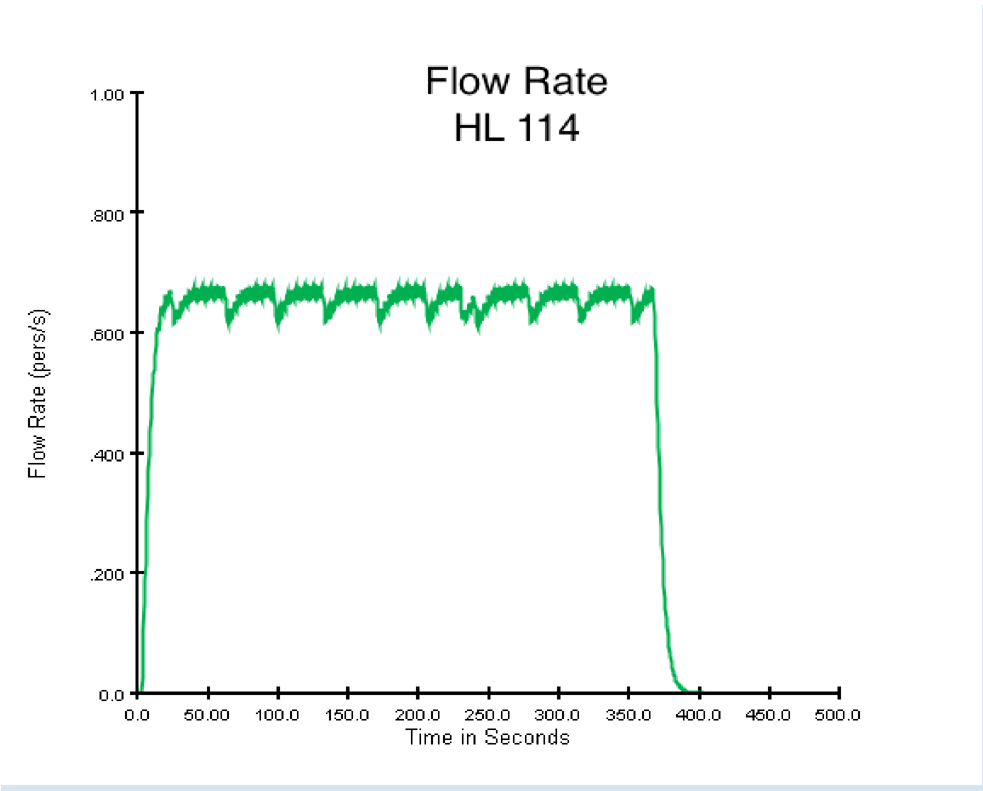


Figure 47 illustrates the correlation between the number of occupants in the queue and their respective queue time through exit access A of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 47: Queue Time All Relevant NFPA 101 Dimensional Limitations Higgins Labs 114

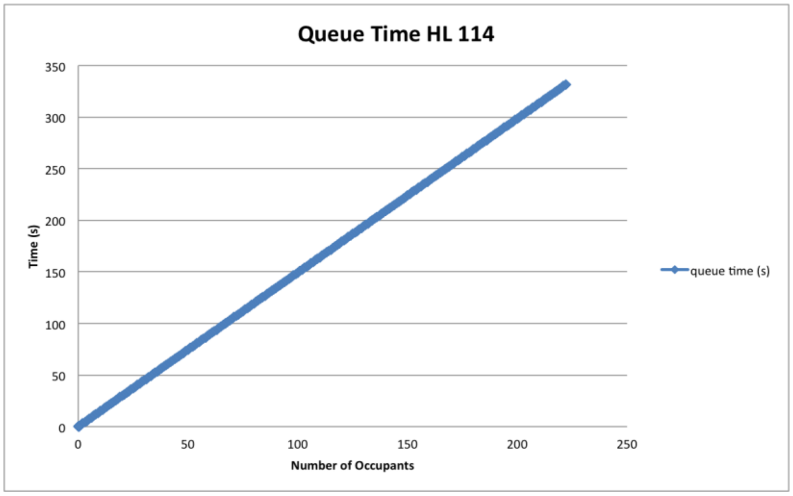


Figure 48 illustrates the instantaneous queue time relative to the total travel time of each occupant in the queue respectively, through the Higgins Labs 114 exit access of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 48: Instantaneous Queue Time All Relevant NFPA 101 Dimensional Limitations Higgins Labs 114

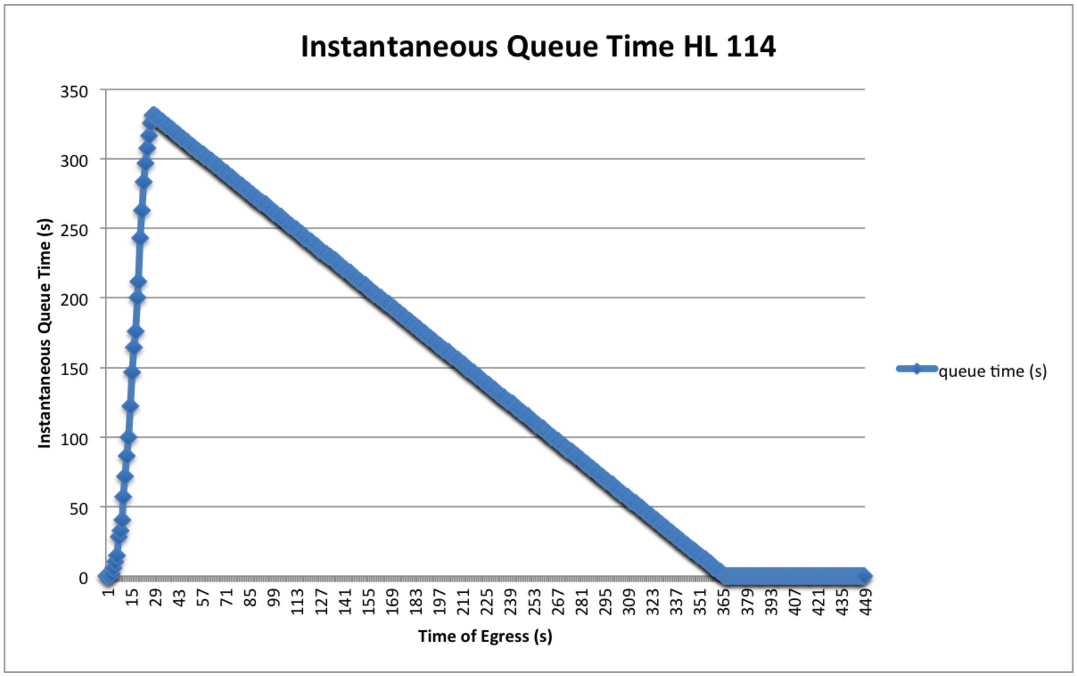


Figure 49 illustrates the flow rate through the Exit 1 of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 49: All Relevant NFPA 101 Dimensional Limitations Higgins Labs Exit 1 Flow Rate

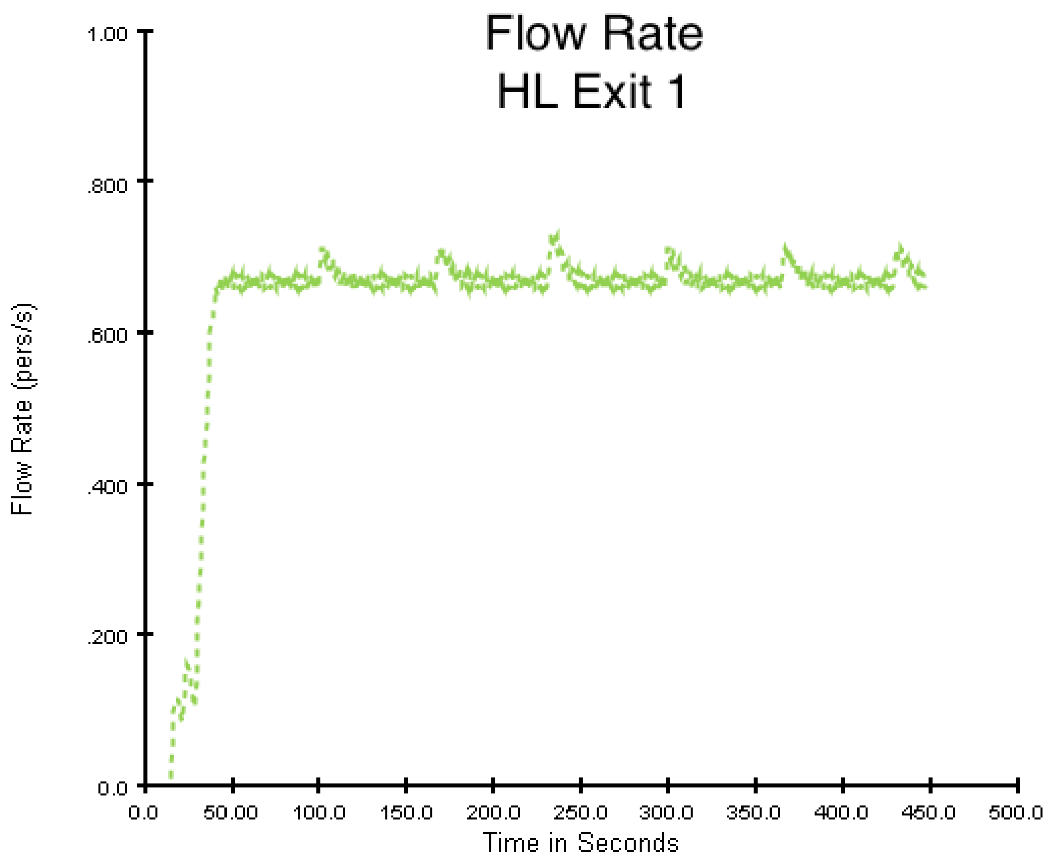


Figure 50 illustrates the correlation between the number of occupants in the queue and their respective queue time through exit 1 of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 50: Queue Time All Relevant NFPA 101 Dimensional Limitations Higgins Labs Exit 1

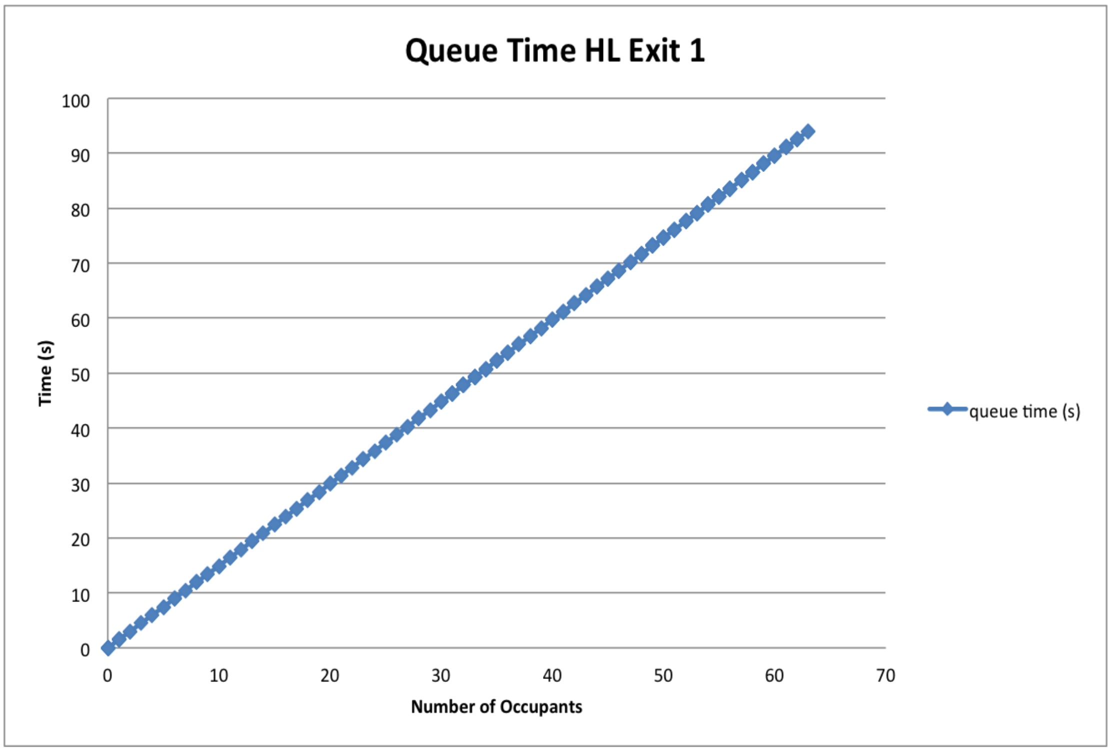
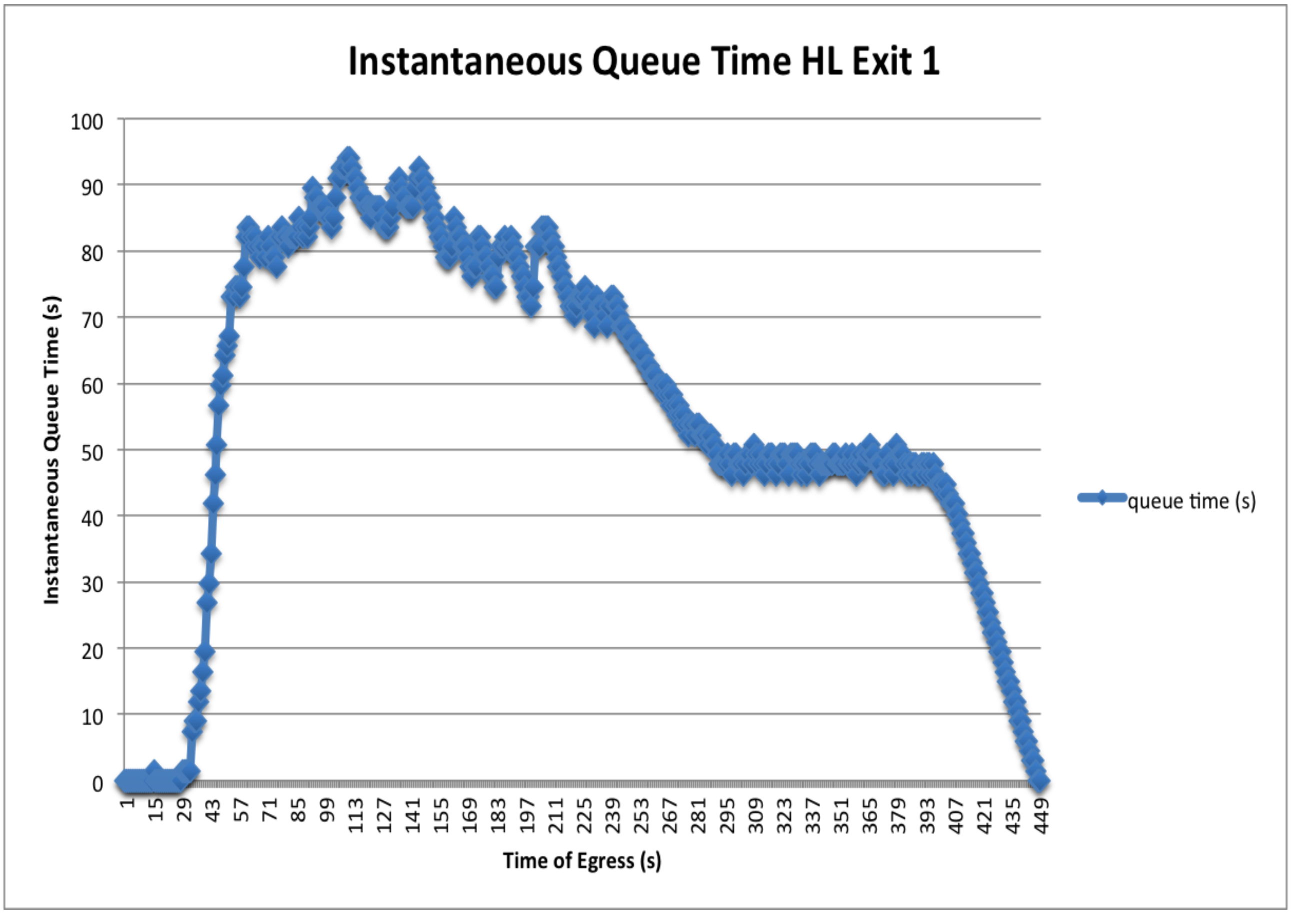


Figure 51 illustrates the instantaneous queue time relative to the total travel time of each occupant in the queue respectively, through Exit 1of the Higgins Labs floor plan when all dimensional limitations are incorporated during the Pathfinder simulation. This information is used to determine the queue time at this specific location. Further discussion and analysis is provided in section 5.

Figure 51: Instantaneous Queue Time All Relevant NFPA 101 Dimensional Limitations Higgins Labs Exit 1



5. Discussion and Analysis

We broke down our discussion and analysis of the entire project into the following categories in order to justify each step and decision made:

- 5.1 Walking Speed
  - 5.1.1 Literature Search
  - 5.1.2 Fountain
  - 5.1.3 Higgins Labs
  - 5.1.4 Hand Calculations
  - 5.1.5 Conclusion
- 5.2 Assembly Occupancy Observations
  - 5.2.1 Higgins Labs 116
  - 5.2.2 Higgins Labs 116 to Floor Exits
  - 5.2.3 Conclusion
- 5.3 Hand Calculations
- 5.4 Pathfinder
  - 5.4.1 Pathfinder Behavior
    - 5.4.1.1 Number of Occupants
    - 5.4.1.2 Occupant Location
    - 5.4.1.3 Occupant Travel Path Choice
    - 5.4.1.4 Why Steering vs SFPE
    - 5.4.1.5 Pathfinder vs Observations
    - 5.4.1.6 Pathfinder vs Hand Calculations
  - 5.4.2 Pathfinder Scenarios
    - 5.4.2.1 Current Higgins Labs First Floor Plan
    - 5.4.2.2 Scenario A: Maximum Common Path Of Travel
    - 5.4.2.3 Scenario B: Minimum Hallway Width
    - 5.4.2.4 Scenario C: Minimum Door Width
    - 5.4.2.5 Scenario D: Minimum Number of Exits
    - 5.4.2.6 Scenario E: Maximum Travel Distance to Exit
    - 5.4.2.7 Scenario F: Maximum Occupant Load
    - 5.4.2.8 Scenario G: All Relevant NFPA 101 Dimensional Limitations
  - 5.4.3 Queue Time

5.1 Walking Speed

Before beginning our sensitivity test, we had to determine a final average walking speed as described in both section 3 and 4. After reviewing the results from our literature search, observations, and SPFE calculations, we ultimately decided to trust the walking speed calculated from the SFPE model. Each walking speed that was taken into consideration for the final walking speed is evaluated below.

5.1.1 Literature Search

The Portland State University study focuses on the travel speed of pedestrians in an outdoor setting. Here, the motion of individuals and crowds is more sporadic versus the restricted motion of occupants within a physical building. This information is used to compare the free fluid-like motion of pedestrians in a more open setting to the slower crowd movement of occupants navigating a building during egress. The Japanese study we focused on from the SFPE handbook found an average walking speed for able-bodied adults walking with another person inside two shopping centers.

Comparing the data from travel speeds recorded in an outdoor setting to those observed inside a building provides insight to the effects of limiting the freedom of motion. As motion is restricted and occupant flow is constricted by various building elements, the travel speed of an occupant decreases.

5.1.2 Fountain

It was important to note the different levels of speed due the different types of people, urgency, and awareness they were experiencing. For example, those who were in groups tended to be traveling at a slower pace than those who were walking alone. The location was also an important factor to look into when analyzing the average walking speed. This observation was taken in an outdoor setting, giving the walkers more space to spread out compared to being inside a building. At no point were the occupants exposed to true danger or aware of our observations.

5.1.3 Higgins Labs

Similarly to the fountain experiment, we recorded whether or not the walkers were in groups or traveling alone. They were unaware of the observation and not in any true danger in an indoor setting. Even though the building had the ability to confine movement, we noted from our observations a low density, such that occupants could move freely through the building.

5.1.4 Hand Calculation

Using the equations for timed egress developed in the SFPE Handbook, we calculated a walking speed of 0.965 m/s. This is further discussed in Section 5.3 below.

5.1.5 Conclusions

We ultimately concluded the walking speed of 0.965m/s, as found in our SFPE hand calculations, as the average walking speed in each Pathfinder sensitivity test. We have the most confidence in this value because we trust that the SFPE model provides the closest travel speed to that of an occupant in an egress situation opposed to the studies found in our literature search and observations, which were not fire situations.

5.2 Assembly Occupancy Observations

5.2.1 Higgins Labs 116

We observed the egress of occupants inside of HL 116, Figure 6, to the exit access doors and recorded travel times over the course of 16 observations, making sure to note the time it took for the first and last occupant to exit the room. As explained in section 3, we discounted outlier occupants, which included any occupants that did not immediately react and begin leaving upon dismissal from the professor or those occupants who exited out exit access C. During the observations, none of the occupants were exposed to danger at any time and were unaware of our observations. Therefore, the occupants felt a very low amount of urgency besides the desire to leave the classroom. This created a noticeably slower occupant walking speed and produced slower times than the hand calculation and pathfinder results. In turn the resulting time observed for the last occupant from HL 116 to leave either exit access door averaged out to approximately 120 seconds.

5.2.2 Higgins Labs 116 to Floor Exits

While recording the travel time of the last occupant to leave HL 116, we also recorded the time of the last occupant to reach the floor exits. We began timing once the first occupant entered the hallway from either exit access A or B and stopped timing once the last occupant reached either exit 1 or modified exit 2. Similar to the egress of the classroom, those leaving the classroom in pursuit of the floor exits felt no urgency and were not in any immediate danger. As a result, the average amount of time observed to reach the exit is also noticeably slower than the times given in the hand calculations and Pathfinder at 113 seconds.

5.2.3 Conclusion

Our group concluded that the results of our observations are not representative of a fire egress situation. It was difficult to compare the times and provide insightful analysis on an travel time for the real life occupants due to the lack of danger and urgency to leave the building. However, we noticed a number of behavioral patterns and tendencies of occupant's movement. We observed that students would often slow down and converse with other students, causing them to walk at a reduced walking pace which increased the overall time for occupants to reach the exit access door and exit door. Each of the 16 times we observed occupants leave HL 116, at least 75% of the students would exit through exit access A and exit using exit 1 as that was their desired way to exit. In addition, several of the students who left HL 116 using exit access B ended up exiting through exit 1 as opposed to the modified exit 2.

5.3 Hand Calculations

Using the equations for timed egress developed in the SFPE Handbook for Fire Protection Engineering, a timed egress study was performed through a multiple step hand calculation.[6] These calculations provide the ability to determine an estimate of the time needed to egress and also a walking speed. For simplicity, a timed egress study was performed on a modified version of HL 116 and the adjacent hallway leading to exit 1 of Higgins Labs. By modifying HL 116 to only include aisle accessway I and exit access A, we eliminated the need to make assumptions as to how many occupants went through either aisle accessway and either exit access. Following NFPA 101, we could assume that 50% of the occupants traveled through aisle accessway I and 50% through aisle accessway II, as depicted in Figure 4. We can also assume that 50% of the occupants traveled through exit access A and 50% of the occupants traveled through exit access B, also depicted in Figure 4. These assumptions will result in an travel time and walking speed specific to this situation. However, we observed that over 75% of the occupants on average would travel through aisle accessway I and use exit access A, while less than 25% of occupants would travel through aisle accessway II and exit access B. Following the SFPE calculation model under these assumptions will result in a different walking speed and travel time specific to this situation. There are several different assumptions that can be made towards the split of occupants travel path choice. For this reason we decided to eliminate the need for assumptions and only allowed occupants to travel through aisle accessway I and exit access A. This created a consistent and reproducible calculation. Similarly, the adjacent hallway was modified for the same reason as HL 116 to only allow occupants to travel through exit access A and exit 1.

The density is then used to calculate the speed at which the occupants can travel through the egress route. For this reason, the density of occupants was determined within each aisle. The speed of each occupant is determined within the aisle. Density and speed are inversely proportional and therefore as the density increases speed decreases, causing occupants to move slower and require more time to escape. However, density becomes very influential when determining the flow through certain points along the egress route. The specific flow is calculated, but remains a measurement of flow per unit of effective width. Finally to determine the calculated flow rate through the aisle, the specific flow is multiplied by the effective width. This width represents the maximum usable width in the aisle. The aisles are spaced as a distance of 32 inches but the chairs prohibit movement throughout the entire width of the aisle. The effective width of 23 inches is used to account for the difference between the maximum usable width and the section of the width taken up by the chairs. Together the specific flow multiplied by the effective width determines the calculated flow rate through each area of interest.

Calculating the flow of the aisle accessway once the occupant gets out of the aisle is the next step in the egress study process. Following the SFPE calculation model, we determined from these calculations that the flow within the aisle accessway was slower than the flow through the aisles.[6] The flow rate of the aisle accessway becomes the governing flow when the two flows converge. While all occupants are in the aisle, their movement is calculated using the aisle flow rate. Only when occupants move into the aisle accessway do the flows of each row converge causing the flow rate to decrease to that of the calculated aisle accessway flow rate.

Going through the calculation process, one occupant is able to travel into the aisle accessway before the aisle accessway flow rate dominates. At this time, the flow rate within the aisles also changes due to the backup of occupants in the aisle accessway, and from here on the movement of the occupants in the aisle accessway and the remaining occupants in the aisles is governed by the aisle accessway flow rate.

The convergence of 7 aisles, each containing 8 occupants, into aisle accessway I creates a situation in which the aisle accessway causes a queue to form. This results in a queue, in which some occupants must wait in the aisle until there is space available in the aisle accessway for them to enter. The SFPE egress study model gives precedence to the occupants furthest from the exit. Relating that to the timed egress study of HL 116, the remaining occupants from the aisle furthest from the exit access A, aisle 7, are given the right of way. Occupants in all other aisles are required to wait in a queue until space becomes available to enter the aisle accessway. The queue of an aisle is determined by the time required for occupants from the preceding aisle to move through the aisle accessway just past the aisle where occupants are waiting in a queue. Finally, one more factor is checked against the flow rate of occupants through the aisle accessway. The exit access door has a unique flow rate but is neglected because it is faster than the governing flow rate of the aisle accessway. Once all the individual calculations are completed, adding up all the times to calculate the total time required to escape completes the timed egress study for HL 116.

Similarly, the SFPE calculation model was used to determine the time required for occupants to travel through the modified hallway adjacent to HL 116 leading to exit 1.[6] For the reasons stated above the hallway was modified to include only exit access A leading to exit 1. However because the flow of occupants originates in HL 116, it must be determined if a governing flow rate exists that will constrict the exiting flow. It is already known that the flow through the HL 116 exit access A does not constrict the flow of occupants from within HL 116. The only other point at which the flow may be constricted is exit 1. The calculated flow of exit 1 is faster than the governing flow from within HL 116. Therefore the governing flow of aisle accessway I also governs the flow of occupants through the hallway. Using the speed at which occupants exit HL 116 and the total distance to exit 1, the time required for each occupant to travel to the exit is calculated. Finally this is combined with the time required for the flow of occupants to travel through exit 1 to determine the total time required to travel through the hallway.

5.4 Pathfinder

5.4.1 Pathfinder Behavior

5.4.1.1 Number of Occupants

All of our Pathfinder simulations on the first floor of Higgins Labs except for the maximum occupant load and “all relevant NFPA 101 dimensional limitation” had a base occupancy of 142 occupants, which was the observed average number of occupants. The purpose of having 142 occupants was to ensure the change in travel time was due to the factor being isolated, not due to the change in the number of occupants. The number of occupants was assigned as 142 based on our observations of the average number of occupants on the first floor of Higgins Labs throughout the day. To start, we found an average of 56 students inside HL 116 from our observations. In addition, there are two smaller classrooms on the first floor of Higgins Labs, which we observed to have an average of 15 students per classroom. There are also lab rooms where we observed approximately 10 students spread across the three rooms throughout the day. The lobby area outside of HL 116 also holds several students waiting to enter for their next class. We accounted for 15 students in this area based on our observations of HL 116. Lastly, the business offices and conference rooms were noted to have on average one person per room and the Mechanical Engineering main offices always had 6 people working there at a time.

5.4.1.2 Occupant Location

Before inputting the occupants into the pathfinder simulation, all of the floor plans and NFPA 101 code limitations models were created. Instead of trying to assume where each occupant on the first floor was located, we used Pathfinder's random occupant location option, to place the occupants. The location of occupants was not a completely random output, but it did place occupants within the area range we provided to Pathfinder. Each occupant placed in the simulation is given a boundary layer of 0.15 meters, as defined by Pathfinder, so as not to have people overlapping with each other. We found this occupant output in Pathfinder plausible because of how occupant location can change daily. This created slight differences in our occupant placement in each model we created, which could have slightly affected the travel time.

5.4.1.3 Occupant Travel Path Choice

Pathfinder allows the user to set the travel path of an occupant by allowing the user to draw out which exits and exit access doors the occupant will egress through. This feature would be useful if we wanted to emulate what NFPA 101 states about exits and exit access doors having to be able to take half of the occupancy through each set of doors available. However, human behavior doesn't necessarily result in occupants splitting evenly amongst two doors, and we observed this through our observations of HL 116. Each of the 16 times we observed the egress of HL 116, an average of roughly 75% of the occupants used exit access A. Taking that into account, we believe that not setting the occupants travel paths to split half and half between the exit access doors of HL 116 was the best way to run simulations.

5.4.1.4 Why Steering vs SFPE

Steering mode and SFPE mode were the two different types of occupant behavior that Pathfinder allows its occupants to have. To reiterate, our team ended up using steering behavior mode because it gave the strongest representation of our observations on occupant movement and provided the closest times with our hand calculations. The reason we did not use SFPE mode for our simulation times is because there is no collision detection option and human behavior is unrepresentative of our observations. Previously in the 2013 version of Pathfinder, SFPE mode had a collision detection option but in the 2015 version of Pathfinder that we used, there is no collision detection option for SFPE mode. However, data pertaining to the queue time of occupants is only provided in SFPE mode. Therefore we did use SFPE mode to calculate queue times. SFPE mode stacks occupants into a doorway and provides the numbers needed to calculate individual queue whereas steering mode provides a real life queue where occupants are waiting behind one another.

5.4.1.5 Pathfinder vs Observations

After multiple observations of occupants evacuating, our group realized that Pathfinder simulations would provide more realistic travel times for a fire situation. Pathfinder assumes that from the moment the fire alarm goes off, occupants will stop what they are doing and begin exiting the building. This is ideal for our goal of identifying the amount of time needed for an occupant to be considered safe based on the NFPA 101 dimensional limitations assuming an immediate occupant response. Occupants from our observations felt no real sense of urgency or danger and would converse with other occupants before actually leaving HL 116. This resulted in an average observational travel time of 120 seconds as opposed to Pathfinder's time of 71.8 seconds for the first occupant to move to the last occupant to reach the exit access of HL 116. However, we did make use of our observations in noting the average number of occupants in HL 116 and the occupant movement patterns that occurred throughout our observational period.

5.4.1.6 Pathfinder vs Hand Calculations

It was decided early on that a multiple step hand calculation timed egress study would become very complex and difficult to execute for the entire first floor of Higgins Labs. The group decided to use the computer simulation software Pathfinder to run timed egress studies of the entire first floor. With the use of Pathfinder, the complexity of numerous hand calculations and the risk of a miscalculation is greatly reduced.   Using the current layout of HL 116 and the adjacent hallway, a full-scale mockup was created in Pathfinder. Using the same parameters as the timed egress study, 56 occupants were dispersed throughout the 7 aisles, and given an input speed of 0.965m/s, the same as the calculated value. HL 116 was modified so that exit access A was the only remaining door available and all occupants were restricted to move through aisle accessway I only. Similarly the adjacent hallway was modified to include exit access A and exit 1 only. By restricting the flow of occupants through these specific areas, the times egress study was simplified to improve accuracy.

Following these same modifications, the mockup of Higgins Labs within Pathfinder was adjusted as to resemble the layout used for the hand calculations. This guarantees that Pathfinder will run a simulation under the same conditions as the hand calculations. Running the simulation in steering mode for the reasons previously explained, the time required for all occupants to escape HL 116 was only 1 second faster, a difference of roughly 1%. Similarly, the amount of time required for all occupants to travel through the adjacent hallway was 8 seconds faster, a difference of about 10%. With such simple equations, it is difficult for the SFPE model to account for a variance of human movement patterns. Through complex modeling SFPE has designated the specific “a” and “k” constants used for each scenario, but human motion and behavior, is extremely dynamic to the point where constant variables can only provide an estimate. On the contrary, Pathfinder uses numerous algorithms that allow the calculation process to continuously adjust for different human motions and behaviors.

The SFPE timed egress study model is useful in generating travel time estimates quickly and without the hassle of creating a building mock-up in a computer simulation software. However, these equations are unable to account for instantaneous variances in human behavior and motion. Further research regarding the derivation of the SFPE model may reveal possibilities to increase the dynamics of the model to match that of human behavior and motion.

5.4.2 Pathfinder Scenarios:

This section discusses each scenario individually. Please refer to Table 31 for a summary of all numerical results.

5.4.2.1 Current Higgins Labs First Floor Plan
5.4.2.2 Scenario A: Maximum Common Path of Travel
5.4.2.3 Scenario B: Minimum Hallway Width
5.4.2.4 Scenario C: Minimum Door Width
5.4.2.5 Scenario D: Minimum Number of Exits
5.4.2.6 Scenario E: Maximum Travel Distance to Exit
5.4.2.7 Scenario F: Maximum Occupant Load
5.4.2.8 Scenario G: All Relevant NFPA 101 Dimensional Limitations

5.4.2.1 Current Higgins Labs First Floor Plan

As a basis for our Pathfinder sensitivity comparison, the current floor plan of Higgins Labs was simulated to get a control time. No changes were made from the current floor plan, and occupancies of each room were determined by observations. It was observed there were 56 occupants in a lecture hall, 15 occupants in the lobby area outside of lecture hall, 8 occupants in the mechanical engineering office, 18 occupants in the professor's' offices, 30 occupants in the two smaller classrooms, 13 occupants in labs and conference rooms, and 2 occupants in the bathrooms for a total of 142 occupants on the entire first floor of Higgins Labs. A time of 80.9 seconds was recorded while simulating the current floor plan in steering mode.

5.4.2.2 Scenario A: Maximum Common Path of Travel

The NFPA 101 limits the common path of travel to 75 feet for assembly occupancies and 100 feet for business occupancies. The only areas in Higgins Labs affected by a common path of travel were the professor's offices. To simulate this factor the hallways in this section of the building were extended to meet the maximum 100 feet requirement. Only these areas are affected because all other rooms are located along a main corridor in which multiple egress options are available at all times. Therefore these areas remain unadjusted from their original location. The changes only slightly affected the travel time of the occupants. The maximum common path of travel took 78.1 seconds for the occupants to exit, which is 2.8 seconds less than the current floor plan at 80.9 seconds. This is a 3.5% decrease in occupant travel time. The occupants in the lobby area had more time to exit before the occupants of the offices reached the lobby area, reducing the amount of crowding and queue time.

5.4.2.3 Scenario B: Minimum Hallway Width

Changing the hallway width to the minimum of 44 inches set by NFPA 101 had a negligible effect on the travel time when compared to the current floor layout. The difference between the time needed for the last occupant to reach the floor exit in comparison to the current floor plan was only 1.3 seconds, a 1.6% increase in travel time. Hallway width had a minimal effect on occupant travel time because the density of occupants was such that the occupants moved unrestricted through the hallway. Also the queue inside HL 116 was not affected by the change in hallway width. This remained the dominant queue in the simulation having the most influence on the travel time.

5.4.2.4 Scenario C: Minimum Door Width

Door widths in assembly and business occupancies are required to be a minimum of 32 inches according to NFPA 101. When the door widths were set to the minimum width determined by NFPA 101 the travel time increased slightly compared to the current floor layout.

It took 3.2 seconds longer for complete egress with the minimum door widths than the original floor layout with a time of 84.1 seconds compared to 80.9 seconds. This is a 4.0% increase in occupant travel time. Reducing the widths of the doors caused more crowding and increased queues times at these doors compared to the original floor plan, especially at exit 1. This crowding caused more occupants to use exit 2 instead of the exit 1.

5.2.4.5 Scenario D: Minimum Number of Exits

NFPA 101 requires a minimum of two exits in assembly and business occupancies. We decided to eliminate exit 2 and 4 from the building and to keep exits 1 and 3. This decision was made because most of the occupants used exit 1 with the original floor plan and exit 3 was needed to fulfill exit distance requirement for occupants on the opposite side of the building. Decreasing the number of exits to the amount required by NFPA 101 resulted in an increase in travel time. With the minimum number of exits it took 103.1 seconds for the last person to egress Higgins Labs, which is 22.2 seconds longer than in the current Higgins Labs layout. This is a 27.4% increase in occupant travel time. Reducing the number of exits caused an increase in crowding and queue times of occupants exiting. There is the same number of occupants as the original floor plan trying to get out of fewer doors, causing this increase in travel time.

5.2.4.6 Scenario E: Maximum Travel Distance to Exit

The travel distance to an exit is the total distance an occupant has to travel until they safely reach an exit. The NFPA 101 limits the maximum travel distance in both a business and assembly occupancy to 200 feet. Extending the hallways, adjusting some classrooms, and adjusting the business occupancies from the current floor plan achieved this maximum of 200 feet for travel distance. When the travel distances to an exit where set to the maximum length allowed by NFPA 101, there was a large increase in travel time when compared to the current layout. At the maximum travel distance to an exit, the time required for the last person to egress was 113.7 seconds, which is 32.8 seconds longer than the time of 80.9 seconds it takes with the current floor plan. This is a 40.5% increase in occupant travel time. Although the number of occupants and occupant travel speed were kept constant from the original floor plans, the distance each occupant had to travel was increased which caused the time needed for egress to increase. Even though the travel distance increased, crowding of the occupants evacuating was unaffected from that of the current floor plan.

5.2.4.7 Scenario F: Maximum Occupant Load

To simulate the effect maximum occupant load on travel time, we assigned the maximum number of allowable occupants to each room. This is determined using the occupant load factor for different occupancy types as defined by NFPA 101 and area of each room. Totaling to 366 occupants, the time need for the last person to reach a floor exit jumped from 80.9 seconds to 117.3 seconds, a 45% increase. This factor had the greatest impact on travel time over all other factors. We realized queue times were playing an important role in the delayed egress and decided to further research the specific queue times of the first floor. The queue time causes occupants to stall at the exits of various rooms, creating a bottleneck effect entering the hallways. The queue time becomes longer as the number of occupants increase, further delaying the ability for all occupants to reach the exit. The congestion started to build at exit 1 around 10 seconds into the simulation. When the backup became visible to the other occupants leaving HL 116, as soon as 13 seconds, they decided to head to exit 2, that was a further distance away but had a wider hallway and less occupants. Exit 1 crowded so quickly due to the fact that multiple classrooms and offices exist in close proximity with their maximum allowable occupancy.

When compared to the current layout egress, the congestion and queue times with maximum occupant load were greater due to the larger number of occupants. The occupants were placed randomly within the classrooms for each scenario, possibly adding to the time difference, although this would only change the travel time within Pathfinder by a few seconds. Most of the congestion occurred within HL 116 when occupants were leaving their seats and entering the aisle accessway. The only exit door with significant congestion and queue times was exit 1.

5.2.4.8 Scenario G: All Relevant NFPA 101 Dimensional Limitations

When all of our identified factors were set to NFPA 101 limitations, the time it took the last person to leave the floor jumped from 80.9 seconds to 500.7 seconds. This was a 519% increase from the original travel time, and was a result of the longest possible distance, the minimum amount of exits, the smallest door and hallway widths, and the maximum occupant load As a result, only exit 1 and 3 remained on the floor with 44in hallways, 32in door openings, 200ft to the nearest exit, and 794 occupants. The walking speed was held constant at 0.965 m/s during the tests. At the beginning of egress, occupant congestion immediately occurred. As the congestion increased, the queue time to reach the exit became significantly longer. After 21.5

seconds, some occupants attempting to use exit 1 made the decision to abandon the use of that exit and attempt to egress through exit 2, even though the travel distance was further. This is because there was less congestion at exit 2 allowing occupants leave continuously.

When compared to the current layout egress the total amount of congestion and queue times were much less. There are many reasons for this, one being the number of occupants. When the HL first floor is increased to its maximum dimensions within code limitations, the maximum occupant load increases significantly by 652 occupants. The drastic increase in occupants is not proportional to the difference in hallway and doorway widths, as well as travel distance to exit, resulting in extreme congestion.

5.4.3 Queue Time

After applying the NFPA 101 dimensional limitations to Pathfinder, individually and all together, it was observed that queue time is one important aspect of travel time that is not directly addressed in NFPA 101. Queue time was not considered a specific sensitivity scenario because it is dependent on each egress situation. However, in each egress scenario, multiple queues develop and play a large role in the overall travel time. Due to our observations of occupants spending exorbitant amounts of time in queues, we felt the need to separately analyze the importance and role queues play in egress. When too many occupants converge to one area, a queue time develops forcing occupants to wait until the area is clear of other occupants. When all relevant dimensional factors were incorporated, the queue times for certain areas increased significantly. Three areas that showed the largest queue times were exit access A, the exit access of HL 114 and exit 1 of Higgins Labs. The queue time of an occupant is a significant aspect of the total time required to reach the exit, but is more important in understanding how long an occupant remains trapped in one area. Focusing on exit access A of HL 116, the exit access door of HL 114 and Exit 1 of Higgins Labs in both the original layout and when all factors were combined, queue times were calculated for each area.

Originally it appeared that Pathfinder provided information regarding the queue time of occupants at each location. However further understanding of the data clarified that Pathfinder only provides information regarding the number of occupants waiting in the queue. In an attempt to gather more information regarding queue times in Pathfinder, the group reached out to Pathfinder Support inquiring if data for specific queue times had been overlooked. In response, Pathfinder Support explained that the 2015 version of Pathfinder did not have the capability to express the queue time of every occupant at any given time or location during the simulation.

Information regarding queue times is important when considering the movement of occupants through Higgins Labs. The ability of occupants to travel through the building with continuous motion significantly reduces the risk of being trapped in an area of danger. When occupants remain trapped in an area, a queue develops. In the event of a fire or hazardous smoke, the inability of occupants to escape that area can result in serious consequences, including death. More information was needed in order to calculate various queue times. Further exploration of Pathfinder's simulation results showed data for the flow rate of occupants through each door at any given time was discovered. This data was combined with the number of occupants waiting in the queue at any particular moment as defined in the Pathfinder data. Using the constant average of the relative maximum and minimum flow rates through a door and the number of occupants in the queue, a general and instantaneous queue time was calculated for exit access A of HL 116, the exit access door of HL 114 and exit 1 of Higgins Labs. Pathfinder only provides a graphical representation of the flow rates. Without a numerical data set of the flow rate it was difficult to calculate queue times based off of the instantaneous flow rates. The general queue time measures the wait time for the last occupant in the queue of a variable size, and the instantaneous queue time measures the wait time of the last occupant in the queue at every instant during the egress.

Analyses of the queue time graphs reveal important information that must be considered in evaluation of safe egress. The general queue time graphs, for each situation, clearly show a linear relationship between the number of occupants in the queue and the associated queue time. The flow rate controls the proportionality ratio of the queue time to the number of occupants in the queue. Doors with a high flow rate show a low proportionality ratio, where as doors with a low flow rate show the opposite. Simply, a slow flow rate will cause the queue time per occupant to increase following a steep linear slope, and a fast flow rate will cause the queue time per occupant to increase following a shallow linear slope. This relationship provides the ability to accurately predict the queue time for any number of occupants in the queue at any given time as long as the flow rate remains similar to the calculated values corresponding to the specific area. One issue that was discovered in the Pathfinder simulation, while simulating queue times, was the way in which Pathfinder ran the simulations. When set to run in SFPE mode, Pathfinder allows occupants to move through each other and into the designated queue area all at once, where occupants queue until there is space to continue moving in the next area. The queue area cannot be seen in the simulation as anything more than a passageway of infinitely small depth. The fault in this simulation mode is that occupants never queue in a hallway or part of a room constricting the flow in other areas. For this reason, the area of the hallway where an exit access door empties into is generally clear or is not blocked by a preceding queue. This results in a constant flow of occupants through the door that is not characteristic of what was seen during the observations. During the observations, occupants were forced to wait for a queue while still in the hallway, thus having a more profound impact on the queue of other areas and exit accessways in the vicinity of the queue. On the contrary, steering mode with collision detection in Pathfinder simulates a better representation of a queue area. In this mode, occupants are seen waiting for a queue while still in the hallway or classroom. Unfortunately, Pathfinder does not provide data of the number of occupants in a queue in steering mode. If this data were available, the queue times would better represent what was observed visually during the observations.

The instantaneous queue time graphs show the relative placement and severity of different queues during the entire egress process. Only the instantaneous queue time for the last occupant in the queue is represented. Comparing the instantaneous queue time for exit access A between the current HL layout and the combined layout with all factors, the significance and severity of the queue changes drastically. Observed in the original layout, the queue time increases to a max time of just less than 16 seconds with an overall queue existing for just around 40% of the total travel time. However looking at the queue time of the same door, when all the factors were combined, the maximum queue time more than doubles to around 42 seconds, but the queue only exists for about 13% of the total egress time. The increase in maximum time is a result of the increase in occupant load, but more importantly, the data shows that the queue existed only very early on in the egress process. The lack of a queue in this area after roughly 70 seconds gives the remaining occupants the ability to move into the exit accessway and move toward the exit relatively early in the egress process. Focusing on the queue times developed in HL 114, an opposite phenomena occurs. While the maximum queue time increase by a factor of around 20, from 15 seconds to 325 seconds, the importance of this data is the significant increase in queue time compared to the total travel time. The queue time for HL 114 under the current layout of Higgins Labs occupies around 24% of the total queue time, whereas the queue time developed in HL 114 when all factors were combined occupies over 81% of the total travel time. For a majority of the total travel time, some occupants are waiting in a queue unable to move toward the exit. This can significantly increase the danger of occupants waiting in this queue, as their required time to reach the corridor is a majority of the time required to reach the exit. Finally, analysis of the instantaneous queue times for exit 1 of Higgins Labs shows similar results where the maximum queue time roughly doubles from 40 seconds to around 95 seconds. However, there is little variance in the percentage of queue time with respect to the total travel time. In both scenarios, a queue exists for an average of roughly 90% of the total travel time. Either scenario shows that a queue develops at exit 1 for a majority of the total travel time. A queue of this duration could be hazardous if immediate danger is present in or near the vicinity of the queue. More importantly because the queue develops at an exit, immediate danger could potentially block off access to other exits. With nowhere else to exit, the total queue time must be considered when determined how fast a fire or hazardous smoke conditions approach to the queue area.

6. Conclusions and Recommendations

The purpose of our project was to determine which building egress factors addressed by NFPA 101 have the greatest impact on an occupant's travel time in reaching an exit on a floor, and to assess the time allowed to reach an exit on an NFPA 101 compliant floor meeting the maximum dimensional limitations permitted by the code. Versions of modified arrangements of the first floor of Higgins Laboratories, a building on the WPI campus, were used to evaluate the egress factors and calculate travel times.

As a result of our project, we determined that occupant load has the greatest impact on travel time for our floor plan scenarios. Maximum occupant load consisted of 366 occupants in the floor plan layout in which 117.3 seconds was needed for all occupants to travel to an exit. This produced the longest time in comparison to the other factors evaluated, which used the average number of occupants we observed to be present in Higgins Labs. Occupant load had the greatest impact due to the resulting congestion of occupants at aisle ways and doorways making them travel less quickly and causing them to wait in a queue prior to reaching the exit. The longer it takes an occupant to reach the safety of an exit, the more likely they'll be exposed to danger. We concluded that the most influential means to reduce travel time for occupants in a building is to first lower the number of occupants allowed in a building, even if the maximum occupancy is NFPA 101 compliant. The most effective way to reduce travel time would be to increase the occupant load factor allowing less overall occupants in the building, providing the opportunity to reach an exit quicker and therefore more safely.

After combining the relevant egress factors into a single floor plan scenario according to the maximum dimensional limitations as prescribed by NFPA 101 for Higgins Laboratories, we conclude that it takes all occupants 500.7 seconds to reach an exit. This building floor plan scenario is code compliant and deemed safe by NFPA 101. So a conclusion could be drawn that occupants have roughly 500 seconds or 8.34 minutes to reach a point of safety.   However, the dynamics of a fire event would actually dictate the overall level of safety and the maximum time allowed to reach an exit. An analysis of the impact of actual fire events was not within the scope of our project.

Further we recommend additional considerations for supplementary development of travel time calculations

Recommendation 1- Different occupants can have different walking speed based on characteristics such as ability, gender, and age. For our project, we used an average walking speed for able bodied adults throughout all of our Pathfinder scenarios. For future projects, we recommend using a variety of walking speeds in order to more accurately represent the travel time of the occupants.

Recommendation 2- NFPA 101 requires all aisles provide a contrasting marking along treads where its location is not always readily apparent. NFPA 101 also provides standards regarding different lighting and visibility applications, which the hand calculations and Pathfinder simulations were unable to account for. We recommend further research regarding the ability of incorporating these factors into both the SFPE hand calculation model and the Pathfinder simulations to determine their impact.

Recommendation 3- We recommend research into the derivation of the SFPE hand calculation model that may reveal opportunities to increase the dynamics of the model to better match that of human behavior and motion.

Recommendation 4- Pathfinder allows for the ability to manually input the location and path of each occupant. This is an extremely time consuming process and requires the need for numerous assumptions as to the location and egress route of each occupant. We decided to trust the algorithms within Pathfinder to best mimic a real life egress situation in terms of occupant location and route choice. We recommend manually placing each occupant and selecting the egress route for each occupant to simulate different possibilities of egress during a fire.

Recommendation 5- For our project we did not test simulations of blocked or obstructed pathways because it is difficult to emulate the placement of the fire and the many different effects that a fire could have on exit choice and travel time. We recommend analyzing the effect of different blocked or obstructed situations through the use of fire dynamic simulations.

Recommendation 6- During our calculations we determined the occupant load based on our observations. We recommend for future projects to adjust the occupant load based on the number of exits within the building and the maximum number of occupants permitted by the code.

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