ABSTRACT

Title of Document: INCREASED INDIVIDUAL SIZE AND ITS POTENTIAL EFFECTS ON EMERGENCY EVACUATION SCENARIOS

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The increase in human body size due to obesity and overweight conditions is recognized as becoming more prevalent throughout the world. The effect which increased body size and weight has on movement has been examined from a kinesiological and physiological standpoint. Its effect on egress during emergency evacuation has largely remained unstudied.

This study reviews current data on body size using modeling software to examine the potential impact an increase in body size has on evacuation times and whether that impact is significant enough to warrant potential changes to current code and regulatory requirements. The change in body size distribution is analyzed and tests are conducted at increasing body size intervals of 0.025 meters for six different scenarios. Results indicate that an increase of 0.225 meters to a body radius increases evacuation times in simple scenarios between 12% and 72%.

INCREASED INDIVIDUAL SIZE AND ITS EFFECT ON EMERGENCY EVACUATION SCENARIOS

By

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Table of Contents

List of Tables

List of Figures

List of Equations

List of Abbreviations

ASET- Available Safe Egress Time

BMI- Body Mass Index

CDC – Centers for Disease Control and Prevention

USDHEW- U.S. Department of Health, Education and Welfare (predecessor to CDC)

IMO- International Maritime Organization

NCHS- National Center for Health Statistics

NFPA- National Fire Protection Association

NIH- National Institutes of Health

NIST- National Institute of Standards and Technology

RSET- Required Safe Egress Time

SFPE- Society of Fire Protection Engineers

SOLAS- Safety of Life at Sea (Convention)

WHO- World Heath Organization

Chapter 1: Introduction

Calculation of an accurate required safe egress time (RSET) is the general standard within the fire protection industry for an evaluation of life safety. Complicating this RSET time can be complicated and imperfect (Gwynne and Rosenbaum 2016). Coupled with changing demographics and human behavior, this calculation can be very complex which may lead to large margins of error in calculated egress times and potential threats to life safety. For the people of a given scenario to be safe from harm, the RSET must be lower than the Available Safe Egress Time (ASET). Because both RSET and ASET are calculated numbers based on probability, building facilities, populations, and potential hazards there is generally a good chance that both incorporate a level of uncertainty. If the times for both RSET and ASET merge toward one another the risk associated with the scenario increases as the safety margin decreases.

The most elementary method, consisting of a first generation evacuation model, to estimating RSET would be the completion of hand calculations based on the SFPE Handbook (Gwynne and Rosenbaum 2016). In this method people are treated as being homogeneous, with constant speeds, sizes, and behaviors. This is a highly simplified method of estimating evacuation time. As research has progressed the dynamics of human movement has also progressed into an understanding of human behaviors and motivations including social forces (Helbing 1995). These improvements have allowed for the development of advanced computer models which are able to incorporate many features and analyze the process of evacuation in more detail and provide results which have or can be validated against real world scenarios (Gwynne and Boyce 2016). Utilization of evacuation modelling has many applications and is often used in performance-based design applications to analyze life safety (Kuligowski et al., 2010).

Despite the increase in technology and the details which are able to be examined through the computer models, something which remains unchanged is that nearly all the computer evacuation models incorporate data to determine the size and movement of individuals based on John Fruin's work from the early 1970's (Fruin 1970, 1987). While the models typically allow the user to change the individual size, the default setting is often in agreement with the size proposed by Fruin (Thunderhead Engineering 2015, ARUP 2015). Population demographics of the American population have changed over the last forty years, and in a direction that is likely to negatively influence the ability of people to egress efficiently from a space that was designed around movement based on data collected during the 1970's. It is likely that this data is providing us inaccurate results which may negatively influence the safety of the current population.

In 2003 at his remarks during the Pedestrian and Evacuation Dynamics conference Pauls called for further research into how obesity and the lack of physical fitness affects the design of exits as well as evacuation procedures (Pauls 2003). He also mentioned that 35 years prior to that date (now nearly 50 years ago) an estimated three percent of building occupants might not be able to safely evacuate without stopping or assistance. As buildings have grown and rates of disease and obesity have increased, our need for understanding how this affects building egress and what, if anything, should be done in response, has also increased. Some discussion has occurred regarding the age of the data which has formerly been incorporated into evacuation dynamics, and warning of its use in current day scenarios and the possibility of outdated information regarding populations (Gwynne and Boyce 2016).

Though research into human behavior and mobility impairment has been studied and incorporated into many of the advanced computer models, both the National Institues of Standards and Technology (NIST) guidance and the International Maritime Organization (IMO) requirements make no mention of body size (Ronchi et al 2013, IMO 2015). While the computer models are verified and validated for situations including varying walking speeds and exit flows, there is little to no mention of body size as a factor in movement during egress. These verifications have all been based on the default body size incorporated within the model which is generally based on the Fruin suggested body size. The Fruin body size concept is discussed in detail in later sections of this report.

This research considers trends and compiles CDC (Center for Disease Control and Prevention) data on body size, coupling it with research in the Fire Protection Engineering field to examine and quantify the possible impact which could be expected in evacuation scenarios with a population of increasing physical size. The methods involve quantifying body size increase and utilizing modeling software to examine the evacuation times at varying intervals of increased body size during simple simulations. An assessment of the time and body size values are conducted based on the simulation results.

It is important to note that the data collected from the CDC and the National Institutes of Health (NIH) is indicative of the population demographics in the United States of America, and not of the world as a whole. However, the World Health Organization

(WHO) indicates that the number and growth of the population within the Obesity and Overweight categories is a worldwide epidemic (James 2008, WHO 2000).

Chapter 2: Background & Literature Review

2.1: CDC and Demographic Data:

Regardless of sex, race, ethnicity, and age, the mean weight and Body Mass Index (BMI) of the American population has increased significantly since early data collection in the 1950's and 1960's (USDHEW 1962, CDC 2018). The rise of obesity within the population has more than doubled in the last 50 years. Currently the NIH suggests that more than 2 of 3 adults are considered to be overweight or obese, more than 1 in 3 is considered obese, and more than 1 in 20 is considered to have extreme obesity (CDC 2018). Among adults the increase has been drastic, with a mean weight increase of more than 27 pounds. The definitions of each category and discussion regarding categorization is found in section 2.1.1 of this chapter.

Research conducted by the National Center for Health Statistics (an agency predecessor to the CDC and NIH) in 1962 states that the average weight for an adult male was 168 lbs. Data collected between 2011 and 2014 showed the average had reached 195.7 lbs (CDC 2018, Fryar et al 2016). For women the average rose from 142 lbs to 168.5 lbs. That is an increase of 16.5% and 18.6% respectively. While weight has risen, the average height has remained nearly steady, rising just over 1% for both men and women (an average of less than one inch). Though direct information regarding the actual measurements and growth of American waistlines, the indications based on weight, height, and body mass index would suggest that people are occupying more physical space on average than ever before. Table 1 illustrates the growth in weight and BMI based on CDC data between 1962 and 2014 (USDHEW 1962, CDC 2018). Since the early 1960's, the mean BMI for adults has increased by nearly 4 points as shown below.

Table 1: Average height, weight and BMI (USDHEW 1962, CDC 2018)

Men				Women		
	Height (in)	Weight (lbs)	BMI	Height (in)	Weight (lbs)	BMI
1962	63	142	25.2	68.2	168	25.4
2014	63.7	168.5	29.2	69.2	195.7	28.7
% Increase	1.11	18.66	15.87	1.47	16.49	12.99

2.1.1: Body Mass Index

The most common method of standardizing weight with height is to compute an individual's Body Mass Index (BMI). BMI is calculated with the following formula:

$$BMI=(W/H^2)*730 \qquad (1)$$

Where: W= Weight in pounds, H= Height in inches

BMI is then used to categorize a person into a physical classification. For adults the breakdown of BMI's for each category is listed in Table 2 below.

Table 2: BMI Categories (CDC 2018)

BMI	Classification
<18.5	Underweight
18.5- 24.9	Normal Weight
25.0- 29.9	Overweight
30+	Obesity
40+	Extreme (morbid) obesity

The data from Table 1 was combined with CDC data through the 1970's, 80's, 90's and 2000's and was used in creating Figure 1 (Odgen 2004, Fryar 2016, US DHEW 1962).

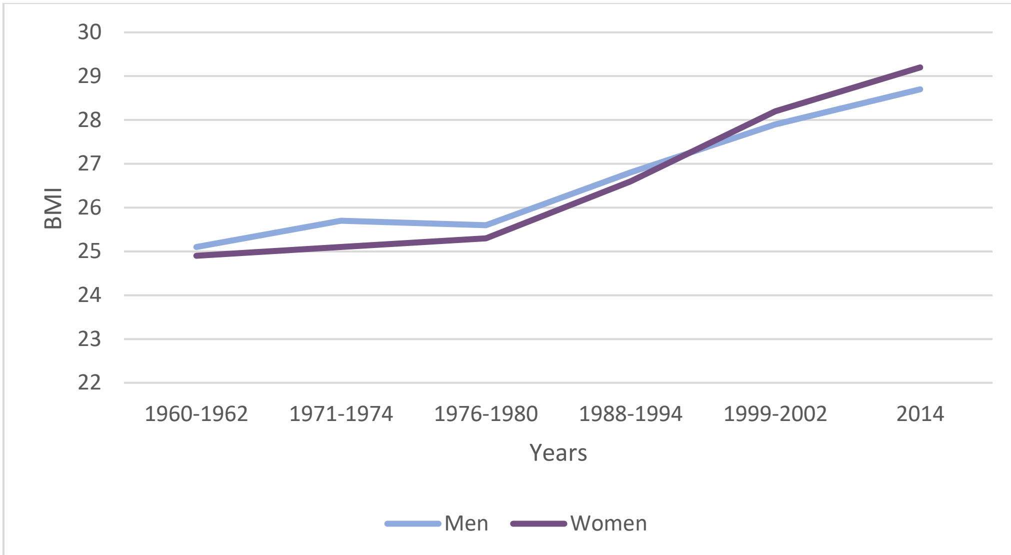

Figure 1: Average BMI 1960-2014

Figure 1 indicates the average BMI's of both genders remain closely aligned and have grown at similar rates, though the rate of increase of BMI for women was slightly higher than that of men. As of 2014, the average BMI of an individual, male or female, was about 29, which indicates that the average person is near the top end of the overweight category.

As would be expected with the growth of BMI over the last half century, the distribution of BMI's has also changed over the years, with people now tending to fall in a higher BMI category than they did in the 1960's.

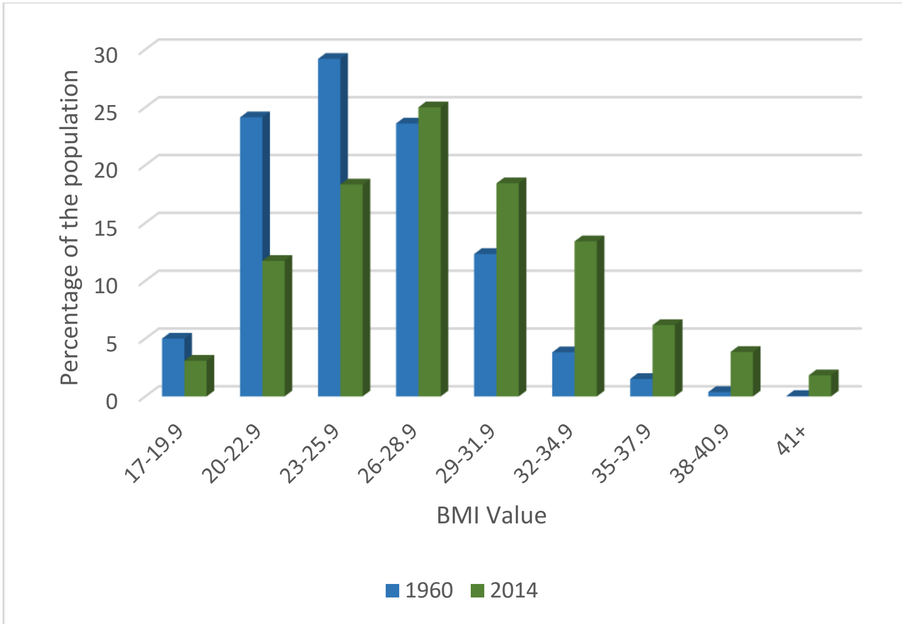

Figure 2: BMI Distribution 1960 v.s. 2014

Figure 2 is based on extrapolated data from the CDC. The number of subjects reported was not consistent from year to year so the chart was formulated to estimate the percentage of the population at different BMI's to illustrate what the potential distribution looked like in 1960 and 2014. It is apparent in the chart that there has been an increase in frequency of occurrence of the upper values for BMI and a decrease of people in the normal to underweight categories. Overall the curve shows flattening and a shift to the right which was largely predicted by research done by the NIH (Penman 2006).

How exactly BMI corresponds to body size is complicated. BMI does not take into account build (other than height) or muscle mass. An indication that someone is obese by BMI standards does not necessarily coordinate directly to body fat or a particular physical size (Prentice 2001). However, it is the most widely used and accepted form of standardizing weight. It is fairly accurate when providing what category a person may fall into with small margins of exception at the edges of each category (Romero-Corral 2008).

It is observed that average BMI's have significantly increased however, the distribution of BMI's become another interesting topic. The number of individuals whose height and weight was reported by the CDC have changed throughout the years, and so it is hard to gain an exact understanding of how the distribution of body masses have changed throughout the years. Previously the curve has been assumed to roughly follow a normal distribution. However, researchers now believe that there is likely a skewing of the distribution curve which shows a shift to the right (upper end) and the possibility that the curve may start to align more similarly to a log normal distribution curve over time (Penman 2006).

In conclusion the increase in BMI and weight is significant and is an indicator that the demographics have changed enough to warrant some further examination utilizing more up to date data.

2.2: Fire Protection Literature

In recent years significant work has been done researching the effects of human behavior and movement in evacuation and fire scenarios. Some examination has been completed for passing movements (Hoskins 2011, 2017), pedestrian dynamics (Pauls 2003; Kholshevnikov and Samoshin 2009; Peacock et al. 2011) and human behavior (Kuligowski 2009; Gwynne et al. 2015) as well as in movement characteristics in stairwells

(Blair 2010; Leahy 2011; Hoskins 2011; Campbell 2012; Kuligowski et al. 2015). The psychological and behavior characteristics have garnered much attention and work has been completed to incorporate current research and refining software models (Qu 2014, Gwynne et al 2015). Additionally, researchers have begun to collect movement and speed data through the examination and compilation of decades worth of work (Gwynne and Boyce 2016). More recently initial attempts to quantify and examine the impact of body size changes (Pauls 2003; Thomas 2014; Thompson et al. 2015, Gwynne and Boyce 2016) have occurred as the understanding of the obesity epidemic has become more established (James 2008, WHO 2000).

The early work within the fire protection literature hinged largely on the investigations of John Fruin and Jake Pauls which was completed through observation of pedestrian movement in the 1960's and 1970's. Though Pauls introduced the idea of the changing demographics and sizes of people over a decade ago, the Fruin data gathered addressing body size in the 1970's is what is mainly incorporated into most contemporary evacuation models along with some updated research on flows and densities (Gwynne and Rosenbaum 2016). Body size analysis has been considered and suggested as a potential factor in movement (Thomas 2014; Gwynne and Boyce 2016) but little has been done to incorporate or collect body size information and incorporate it into pedestrian models. In fact, Thomas looks at research completed by Pauls as well as Predtchenskii and Milinskii regarding clothing influences on body size, densities, and flows (2014). He cites that the information regarding changes in body size due to clothing are potentially indicative of the trends which would accompany an increase in body size. Thomas also suggests that based on the information provided by Predtechenskii and Milinskii a 25% reduction in flow rate would be observed simply because of the increase in size associated with winter clothing (as opposed to summer clothing). In addition, he states that a comparison can be made to children, who show increased movement flows as body size is reduced.

As previously noted, Fruins' work was completed in large metropolitan areas (New York City and Pittsburgh) and primarily amongst commuters. Data collection by New York State, New York City and the CDC shows that New York City has lower rates of obesity and overweight portions of their population (currently at approximately 45%) than the rest of the American population (66%) (CDC 2018, NYC.gov 2018). This would indicate that data collected by Fruin is likely skewed to indicate a smaller body size because of the population surveyed.

The following sections of this chapter will serve as an introduction to the basis of the mathematical analysis of pedestrian movement and serves to show the information which is used. Details incorporated in the fire protection literature form the basis for the pedestrian modelling software. An examination of the literature as it pertains to movement models is contained in the following sections of this chapter.

2.2.1: Body Area

In the fire protection literature, the shape of the human body and the space that it occupies is a foundational concept. A large part of the field estimates the shape of the human body to be in the shape of an ellipse (Fruin 1987; Predtechinskii and Milinskii 1978). The size of the ellipse Fruin reported is 18 inches 0.46 meters in depth by 0.61 meters in breadth. The total area therefore is 0.21 m^2. The typical defaults used in many of the models, particularly those used for this research, are based on values at or close to the ellipse size predicted by Fruin and are discussed further in Chapter 3. It should be noted that nearly all of Fruin's research was conducted in cities, particularly in northern cities (New York being one he studied most) which tend to have significantly lower rates of obesity and overweight individuals (CDC 2018, NYC.gov 2018).

Fruin reported that the adult male human body occupies only a portion on the area he cited and described the ellipse as allowing extra space for pedestrians who are carrying objects, accounting for body sway and incorporating a boundary layer between individuals. Predtechinskii and Milinskii also suggested a body formation as an ellipse which is shown below in Figure 3. According to the picture the ellipse they suggested incorporated only body area and not particular items being carried or a type of buffer zone for boundary layers. They also suggested that the body size fell within a range of sizes which would vary depending on factors such as clothing, gender or the carriage of items.

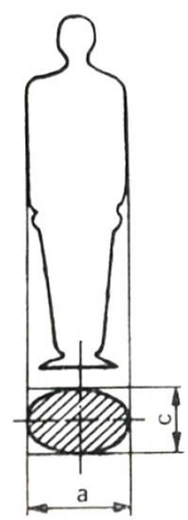

Figure 3: Horizontal Projection of the Area of a person (Predtechenskiĭ and Milinskii 1978)

Utilizing the formula for an ellipse a body size in square meters can be found:

$$f=(\pi/4)a*c \qquad (2)$$

where: a=depth in meters, c=breadth in meters, f=area in m^2

The work of Fruin shows some consistency to the observations of Predtechenskii and Milinskii (1978) who's ellipse area range for an adult varied from 0.1-0.825 m^2 based on the factors discussed above. The average of the range of areas they suggest (particularly the sizes of lighter dress and less gear) is in close alignment with Fruin's reported size. It is important to note that they completed research in the USSR (Russia today) around the same time as Fruin. Similar to the issues of comparing body sizes of residents of NYC to those of other areas Pretechnskii and Milinskii's data is representative of a population in European cities, which in current day may be significantly different than what is common in the general U.S. Population.

2.2.2: Density

The desire for personal space and buffer zones is found in nearly all aspects of human movement and activities. Space required for movement then incorporates what Fruin divided into sections called the pacing zone and the sensory zone (1987). The pacing zone is the area required for foot placement (dependent on age, sex and physical condition), whereas the sensory zone is the area required by the pedestrians for perception, evaluation and reaction (comprised of perceptual and psychological factors). It could also be inferred that the sensory zone could change with a change in physical ability as well as vision and depth perception. All of the above impact on the psychological understanding of a person's physical capabilities and influence the minutia of human movement (Fruin 1987). As a person becomes less mobile or more visually impaired, their movements will change not only in the pacing zone but also could play a role in changing the sensory zone.

Density has been found to be a significant determinant of pedestrian walking speed (Fruin 1987, Predtechenskiĭ and Milinskii 1978). Fruin observed that as traffic density increased pedestrian speed is decreased. Increased density reduces the available free space for a pedestrian to pass a slower moving individual. However recent work has shown that passing is not a common phenomenon (Hoskins 2011). Density may be expressed in three ways as suggested by Predtechenskiĭ and Milinskii (1978):

$$D=N/A \quad (persons/m^2) \qquad (3)$$

$$D=A/N \quad (m^2/person) \qquad (4)$$

$$D=\sum f/A \quad (m^2/m^2) \qquad (5)$$

Where D=Density, A=Area of the flow, N=Number of persons, f=Horizontal projection of ellipse (area)

Equation 5 is the only density expression which allows for the consideration of different body areas in the calculation. In the others the area of an individual is implicitly assumed to be a constant. Densities have been found to vary largely based on the component and utilization of the space. Low densities are normally observed in stairs and higher densities are seen where paths narrow (Fruin 1970). Maximum densities are observed in places such as doorways which are typically the narrowest. Under high densities it is predicted that the differences in speeds which are achievable is limited (based on the density) (Predtchenskii and Milinskii 1978, Pauls 1984). This is confirmed by the works of Fruin who also described densities based on a level of service.

Table 3: Fruin's Level of Service (Fruin 1970)

Level of Service	Space(m^2/ped)	Density (ped/m^2)
A	>3.25	<0.27
B	3.25-2.30	0.43-0.31
C	2.30-1.39	0.72-0.43
D	1.39-0.93	1.08-0.72
E	0.93-0.46	2.17-1.08
F	<0.46	>2.17

It has been observed that above a level of 4 persons/m^2 crush conditions where people are unable to move (Pauls 1984). Part of the problem with establishing divisions for speed and movement in persons/m^2 is that if the size of people increases it would take less persons per square meter to reach the same density (utilizing Equation 5), simply because the larger assumed average size of the individuals.

It is significant to note that Fruin's level of service concept and categories are incorporated into both MassMotion and Pathfinder which are used in this research. It is important to note that the common expression for density is persons/m^2 (occupants/m^2) or its inverse m^2/person. The density used in most movement formulas, particularly in hydraulic calculations (hand calculations) is one that is represented with the units of persons/m^2. This is discussed in further detail in the analysis section of this report.

2.2.3: Boundary layers & Effective Width

Pauls (1984) and Fruin (1970, 1987) compiled research on the distance people would leave between themselves and objects whether it is other people or relative to stationary objects or building features. This concept was briefly introduced in the discussion on density, where it was noted that people will leave space between themselves and other occupants. This boundary layer allows space for movement and is the reason people are not typically seen brushing against walls or doorways as they move within a space.

Boundary layers take away from what is described as the clear width of a space which is the fill distance from wall to wall, or between two other stationary objects. The remaining width becomes the effective width. Boundary layer sizing is well established within the literature and is used consistently throughout hand calculations and within models (Gwynne and Rosenbaum 2016).

$$\boldsymbol{Total\,Width\ -Boundary\,Layer\ = Effective\,Width\,(We)} \qquad \textbf{\textit{(6)}}$$

Along with allowing for space between occupants and between occupants and objects this boundary layer is important in as it accounts for body sway as individuals move. Fruin states that body sway was measured to be about 10.2 cm (4 inches) as weight switches from foot to foot while an individual walks. It is now understood that an increase in body mass also has an impact on balance and sway due to increased midsection weight and a change in center of gravity, however complete understanding of the correlation between weight, body size, and movement (Forhan 2013; He and Baker 2004). Stair widths in multiples of 0.56 meters (22 inches) are incorporated into most building codes are based only on an assumed width of individuals. The regulations historically have not accounted for body sway movements or changes in distributions. Suggestions that intervals of 30 inches would make for more efficient flow of people have been introduced as have cases where increased stair widths could have led to a more efficient flow (Pauls et al. 2005).

Changes in human size may slightly change the boundary layer and spacing distances as described above in the discussion of density. The effects of a small change in boundary layer is likely to have less of an impact than a more sizable increase in body size. It is more likely that as body size increases the number of people that can pass through a given effective width is likely to decrease (with no change to the boundary layer).

For the purposes of this research the boundary layer distances are not adjusted from what is incorporated into the models based on the literature (Gwynne and Rosenbaum 2016; Thunderhead Engineering 2015). The effective width of the building structures will therefore remain the same and will eliminate the potential impact of changing boundary layers.

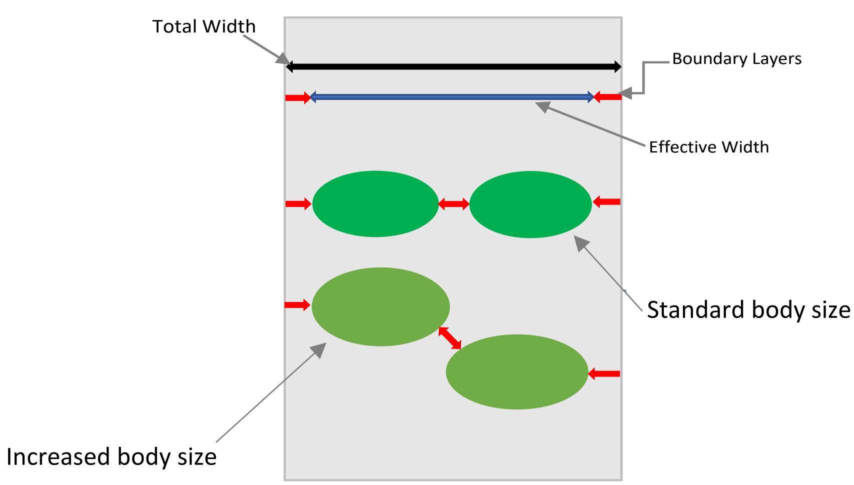

Figure 4: Boundary Layers & Increased Body Size

2.2.4: Speed

In a free flow walking scenario tests indicated that the majority of people walked around 61-76 meters per minute (1-1.3 meters/second or 200-250 ft/minute) on a horizontal surface (Fruin 1987). It was also observed that healthy humans could increase their walking speed by about 40 percent for short durations of time. It should be noted that this study was completed on a horizontal plane with a larger width as the distance from the start location increased. Pedestrians were also tested with no large bulky handheld items or clothing and the number of mobility impaired pedestrians were noted to be low (Fruin 1987). An extensive compilation of data is reported in Chapter 64 of the SFPE Handbook (of Fire Protection Engineering, 5^{th} Edition) by Gwynne and Boyce. The figures and tables presented indicate that speed is impacted by density and that there is a range of speeds which have been previously reported. At densities below 4 persons/m^2 the data presented indicates speeds primarily between 0.5 and 1.5 m/s (Gwynne and Boyce 2016). The data also indicates that the range of speeds observed is larger when the density is smaller. As the density increases the speeds which are observed trend downward.

Fruin also believed that agents' travel speed was a function of the density of the population (1970, 1987). He was able to quantify the speeds in relation to density and create his Levels of Service which are described in the density section of this chapter. As the density population increases the speed will decrease, speed would be expected to decrease as the density increases. By the level of service indicated as F (which is the most dense category suggested by Fruin) very little to no movement is possible and any movement that is seen would be at low velocities as indicated in Table 3.

At very low densities the movement of individuals is not affected by those around them (Gwynne and Rosenbaum 2016). As densities increase the relationship is assumed to be linear with respect to density.

The formula for speed is typically given as:

$$\boldsymbol{S = k - akD} \qquad \textbf{\textit{(7)}}$$

Where: S= horizontal speed, D= Density, k= constant based on the route element(s), a= 0.266 (speed in m/s) or a=2.86 (speed in ft/min)

This equation is reported by Gwynne and Rosenbaum (2016) as having been adapted from the works of Fruin and Predtechenskii and Milinskii. They also establish maximum speeds which would occur at very low densities (below 0.54 pers/m^2).

Data collected and reported in Chapter 64 of the SFPE Handbook, as mentioned above, show a range which includes velocities which are greater than the limit of 1.12 m/s reported to be used in the hydraulic model.

2.2.5: Specific Flow

The flow is the number of persons that can pass a single point along a route, per unit time, per unit of the effective width of a given route. The formulation for specific flow is suggested in the 5th Edition (Gwynne and Rosenbaum 2016) of the SFPE Handbook of Fire Protection Engineering as:

$$\boldsymbol{F = S * D} \qquad \textbf{\textit{(8)}}$$

$$PV = S \div M \qquad (9)$$

Where: F=mean flow rate (persons per m/s), S= mean Speed (horizontal in m/s), D= mean Density (persons/m^2)

PV=mean pedestrian flow rate (m/s per person), M=Average pedestrian Area (m^2/Person)

Peak flow studies indicated that 30 pedestrians per foot of walkway width per minute (PFM) was attainable under most conditions, 25 PFM was attainable under favorable conditions and that 20 PFM was attainable only under the most favorable conditions (Fruin 1987). Predchtchenskii and Milinskii also examined the impact of density on speed and found that for different egress components the speed and density relationship differed with the speeds at the highest densities being greatest for opening and horizontal paths and lowest for descent on stairs. They also clarify that components have a maximum capacity for a given density and speed using the formula below (Predchtchenskii and Milinskii 1978).

$$Q = D * v \qquad (10)$$

Where D = density in pers/m^2, v= speed in m/min, Q= maximum capacity m/min

In the early 2000's Pauls called for additional research in human behavior and group movement (2003). He also indicated that Fruins' ellipse theories worked well in high-density, low-speed situations. Pauls reinforced the relationship of speed and flow to density and acknowledged the increase in human body size as well as the need for research into the influence of the obesity epidemic on pedestrian movement and emergency evacuation.

2.2.6: Controlling Flow

The controlling flow of a given scenario is relevant only to hand calculations and is related to the element of the scenario which will cause the flow to slow the most and thereby create a queue. To establish which element is the controlling element the effective width should be multiplied by an established constant (which relates to the element design) to establish a controlling flow. The controlling flow rate which is the lowest is the one which will be the most restrictive and is the one which will ultimately dictate the flow of the scenario. This is factor is relevant for completing hand calculations per the SFPE Handbook method.

2.2.7: Fatigue

Fatigue is a complicating factor in human movement which has been suggested as a potential factor of evacuation times (Ronchi et al 2015). During a small scale evacuation, it is likely that fatigue would not play a significant role as people appear to not fatigue when movement is required for a short period, regardless of body size (Forhan et al 2013). However, there is some impetus to believe that fatigue in larger scale evacuations where long distances are required for egress within the general population. Notably this work has been reported in buildings where stairwells are concerned (Ronchi et al 2015).

The majority of this work on fatigue as it corresponds to body size, particularly for the body size of people with BMI's in the 'overweight' and 'obese' categories has been done by people in the kinesiology field (Ko 2010, 2012) and is more concerned with the minutia of the movement rather than the movement of the individual from one point in space to another. On one side fatigue is being considered and there are suggestions on how to incorporate it into models (Ronchi et al. 2015; Ronchi 2016). However how exactly fatigue rates correspond to body size and longer evacuations is something that, while pertinent and critical, is difficult to predict and quantify. Suggestions on how to incorporate fatigue have been introduced (Ronchi 2016). As stated by Ronchi the impact of a populations characteristics may play a large role in fatigue, especially in areas where a population may have an increased body size.

Researchers have noted that in cities with high rise building evacuations can be timely and may require an individual to walk down a large number of stairs. There is now understanding that in high rise buildings flow in the stairwells can be slowed as people with mobility issues enter the stairwell and the merging process of floors below (Hoskins 2011, 2017; Campbell 2012; Kuligowski et al. 2015). Solutions for these issues are still relatively recent include topics such as phased evacuations and increasing the use of elevators during egress. Overwhelmingly though the majority of evacuations still require people to take the stairs especially in mid-rise buildings.

There are a multitude of variables that are an issue when looking at stairwell egress (Hoskins 2011). People with permanent disabilities certainly pose an issue, and may be assigned to seek an area of refuge, but there are likely a large number of people that have temporary ailments or fall into a different mobility impairment category coupled with an ever-increasing population that falls within the overweight and obese category the limits of mobility and endurance are likely to be compromised. The exact level at which this effects egress is still largely unknown. The increase in unconventional building design could also add to a fatigue concern as time increases. Upward vertical movement is not as likely to be required for evacuation scenarios but there are underground facilities in which the egress path requires movement up several sets of stairs (Ronchi 2016). It is likely that fatigue would become an even larger issue in upward movement than downward movement.

Chapter 3: Evacuation Models

3.1: Hand Calculations

Though computer models have gained traction and are becoming more recognized hand calculations using the hydraulic method are regarded as the foundation for the evacuation calculation process (Gwynne and Rosenbaum 2016). Many of the formulas and data which are incorporated in the hydraulic method for hand calculations are also incorporated as the basis of the computer models.

3.2: Regulatory Requirements & Suggested Guidance for models

Countries all have differing code requirements for the standards which must be met in order to ensure life safety in evacuation scenarios. In the United States NFPA 101 lists prescriptive code requirements and lists requirements for consideration if Performance Based Design scenarios are to be used. NFPA 101 clearly states that the "capabilities of the occupants" must be considered as well as "Other factors necessary to provide occupants with a reasonable degree of safety".

Software evacuation models are often used with fire models for an analysis of performance-based design. NFPA 101 clearly states in Chapter 5:

" 5.4.5 Occupant Characteristics.

5.4.5.1* General. The selection of occupant characteristics to be used in the design calculations shall be approved by the authority having jurisdiction and shall provide an accurate reflection of the expected population of building users. Occupant characteristics shall represent the normal occupant profile, unless design specifications are used to modify the expected occupant features. Occupant characteristics shall not vary across fire scenarios, except as authorized by the authority having jurisdiction."

Based on the CDC data it is can be understood that people do not fit the size parameters which were established by John Fruin in his pedestrian research during the 1970's and which are incorporated into the current evacuation modelling software. Occupant Characteristics are mentioned many times within the Code. However, occupant size is never mentioned in relation to those characteristics (NFPA 101 2015)

3.3: Computer Model Verification

NIST Technical Note 1822 and MSC.1/Circ.1533 are used as the main guidance for the Verification and Validation of evacuation models.

The MSC.1/Circ.1533 is a guide for implementation of the requirements of SOLAS Regulation II-2/28-1.3 which requires an evacuation analysis for passenger ships. Though it is recognized as a maritime based document and passenger vessels its NIST reviewed and incorporated many of the theories and tests presented in the IMO Circular expanding and modifying it to create guidance related to the verification and validation of models for building use (Ronchi et al. 2013). NIST does not regulate or govern the features of the models which may be verified against the note, it is simply designed as guidance for model creators and building designers to use as an assessment tool in evaluating the applicability of an evacuation software program. In a similar fashion the IMO Circular is a tool which may be used to show compliance with a regulation which is applicable to certain types of maritime vessels (namely passenger ships). The IMO Circular suggests one method and type of showing compliance with the regulation stated in SOLAS.

The IMO circular dictates walking speed as it relates to gender and age. It is important to note that a majority of the tests which are described in the IMO Circular require the use of a "male population from 30-50 years old" as the agents to populate a test scenario. The IMO Circular also dictates the speeds expected of the breakdown of each age and gender grouping. According to the table provided by the IMO the group of males age 30-50 has the 2^{nd} fastest minimum and maximum walking speeds of the 10 groups described. It is interesting that using the men of that age bracket would be likely to yield one of the faster evacuation times than if a population with a slower speed or an average of them all combined would yield.

It is critical to note is that the size of the individuals is not established or mentioned within the IMO Circular and is only briefly noted in the NIST Technical Note by stating that the gender of an individual is not normally prescribed by the model and that changes of gender could be reflected by changing the body size or walking speeds to consider gender (Ronchi et al 2013). Therefore neither the IMO Circular or NIST note give any further guidance regarding analysis based around a larger body size.

Another key note pointed out by many professionals within the field is that while a software system may have been verified to comply with the NIST guidance and IMO requirements, the validation cases which ensure that a model is a sufficiently accurate representation of reality are somewhat lacking (Pauls 2003, ARUP 2015). Data collection within real world situations is limited, and so often a software is compared to hand calculations or another model type.

3.4: Computer Models

Rather than seeking to improve the capabilities of computer models this research aims at quantifying the potential impact which increased individual size has on evacuation and uses the computer models as a tool for the examination process. The majority of evacuation modelling assumptions are based on data from non-emergency movement and is incorporated into the fire protection literature that was discussed in the previous section. It has been found that unless people are in relatively close contact to either fire or smoke they will tend to move in ways similar to those of normal pedestrians (ARUP 2015).

There are a large number of evacuation models on the market. They range in capabilities, features, computational power and human behavior capabilities and assumptions. The simplest of computer models are models which largely mimic hand calculations and base the majority of the basis on the hydraulic model, considering a population as homogenous as it relates to body size, density, and behavior. On the other end of the model spectrum are models which are able to analyze behavior and even simulate artificial intelligence of individual people in a simulation scenario. These more complex models incorporate data and information which has been collected by researchers in the field as the understanding of human behavior and movement has progressed. Computer modeling of evacuation allow for a lot of advantages. Changes within the model are easily incorporated whether it relates to body size, speed changes, or goals. Tests can be run a multitude of times with specific inputs. Human risk is negligible as human subjects are not used (Gwynne et al. 1999). Models have advanced throughout the years, some more so than others, and as such there are a wide variety available for use.

Perhaps the most important feature and consideration for model use as it applies to this research is the type of modeling method which is used. Basic models which only incorporate movement are aptly named movement models (Kuligowski 2016). These models do not incorporate human behavior but show details regarding the flow of occupants. A partial behavioral model would typically involve behavior of the occupants but only to a degree and only which is controlled by inputs of the user. These partial behavioral models allow a user to define a behavior (such as a delayed start to evacuation) (Kuligowski 2016). They also allow a user to dictate other personality behaviors and/or at what times agents will perform certain tasks. Finally, the most advanced type of computer models are behavioral models which are able to account for individual occupant behaviors and incorporate the agent's individual ability to make decisions based on a number of factors which can be completed simultaneously while moving as required for egress. The models may also be advanced enough to have the occupants understand risk (Kuligowski 2016).

Two different computer models are used for this research. The first is MassMotion which is a proprietary software of Oasys, an ARUP owned company. The second is Pathfinder. Pathfinder is available to the public market through Thunderhead Engineering. The two programs differ in some notable ways: MassMotion is a behavioral model, where Pathfinder is only a partial behavioral model; further within those categories MassMotion has behaviors which are both probabilistic and it is able to simulate artificial intelligence and decision making. As an example, within MassMotion the agents are aware of the exits and queue lengths. Occupants would also be aware of available exits and might choose a route over a longer distance because it would lead to a shorter evacuation time if queue lengths were longer elsewhere. Pathfinder incorporates behavior implicitly (Kuligowski et al 2011).

There are commonalities between MassMotion and pathfinder which allow the user to make simple comparisons between the two. Particularly, both have 3-D output views where agents are represented by avatars that have the shapes and movement features of people and both allow for visual mapping of the Fruin levels of service. These “maps” appear as color coded contouring of the “floor” which is occupied by the agents. One big thing to note is that neither Pathfinder or MassMotion allow for the ability to change the mapping of the density to anything other that Persons/m^2 or m^2/Person. The ability to represent density as a m^2/m^2 value show the most variance as people get larger. This density theory is discussed further in a later section.

The details regarding the selection of the software programs and the exact settings are discussed in Chapter 4 as a part of the methodology. Details regarding background information and basic features of MassMotion and Pathfinder are contained in the following sections within this chapter.

3.4.1: MassMotion

MassMotion has been used to assess pedestrian movement and evacuation dynamics in many high-profile design projects. Different types of files can be uploaded into the system as designed and edited to create a model which can incorporate nearly limitless types of movement and restrictions. The human behavior portion of MassMotion includes the synthesis of the behaviors and Helbing social forces methods seems to well represent actual human behavior and movement. MassMotion also utilizes the amount of available space and the number of neighboring agents to calculate density, and is aware of the size, speed and location of neighboring agents (ARUP 2017). As the density of a population increases in MassMotion the speed of an agent will decrease according which following the trends established by Fruin. In MassMotion the density calculation is based on the amount of available space and the number or neighboring agents and density mapping features are available in either persons/m^2 or m^2/person.

Instead of using the Fruin suggest ellipse as a projection of body area, MassMotion assumes the area of a human to be circular (Dabney 2018). The default setting is a radius of 0.25 m which creates a projection area closely aligning with the area of a standard size Fruin ellipse. The standard default setting is a constant area assigning the same agent size to each agent. However, a user may manipulate the sizing and distribute it under other "custom" options. The options for size distribution are constant, exponential, log normal, normal, triangular and uniform (rectangular). As shown by the CDC data most of these types of distributions are not relevant for analysis of the general population. The CDC data and BMI distributions appear to align with most closely with a normal distribution or possibly to a log normal distribution with a right skew (Prentice 2001, Kozlowski 2002).

Selecting a normal or log normal distribution in MassMotion automatically generates default settings. When a normal distribution is selected the default is 0.25 meters for the mean, 0.325 meters for the max, 0.125 meters for the minimum and 0.0625 meters (though MassMotion does not show a unit) for the standard deviation. All of these measurements refer the radius of the individual agent.

Mass motion utilizes a 'repulsive' force to maintain adequate separation between different agents (called the Neighbor force by the developers) and the agents are aware of the other agents which are within a certain distance of them. This repulsive force is coupled with other forces which make a resultant vector which determines the movement of the agent. The other forces that MassMotion considers are Goal, Cohesion, Collison, Drift, Orderly Queuing and Corner (ARUP 2017). All of these forces are combined to create agent movement through a "Social Forces" parameter. The exact formula for the calculation is proprietary to Oasys, but the formulas for movement are based on the Helbing equations (Dabney 2018). The Helbing Equations illustrate what is listed above, that coupling the different "social forces" such as the desire to reach a destination, the desire for personal space, the desire to maintain a separation distance, the influence of density in the immediate area etc., all come together to create a single vector which will determine the movement of the individual in the simulation (Helbing and Molnar 1995, Lakoba and Finkelstein 2005). These forces include forces of desire ($\vec{f}\, goal$) which are assigned by the user and in MassMotion include movements assigned for the purposes of the project at hand. An example is the user assigns the goal of "evacuate" to a population. These goal forces will move the agents in a positive direction toward the goal which has been assigned. Acting in opposition to those forces are repulsive forces ($\vec{f}\, repulsive$). These forces include things such as the desire to maintain personal space or boundary layers. In a very simplistic case $\overrightarrow{f}\,repulsive + \overrightarrow{f}\,goal = \overrightarrow{f}\,movement.$

Agents are also aware of obstructions and of the general building design of the floor they occupy even if they are not within sight distance of an exit they understand that the exit exists. This is perhaps MassMotion's most interesting factor. In real world scenarios, a person may know that another stairwell or exit door exists, but they will be unaware of the wait time unless notified by another individual or building management. In MassMotion, an agent is aware of the wait time even if they can not see the queue (as long as it is the same floor) (ARUP, Dabney 2018).

Coupled with the idea of the forces creating a movement vector for the agent the other essential part of the movement of the agents within MassMotion is the density of the agents. MassMotion incorporated the work of Fruin into the model with the concept that as the density of the agents increased the agents are less mobile and are forced to reduce their stride length when in crowded spaces. MassMotion features capabilities which allow the user to view density instantly as a "map" with the agents or without. This density mapping is only available in Fruins' Level of Service which utilizes the units of persons/m^2.

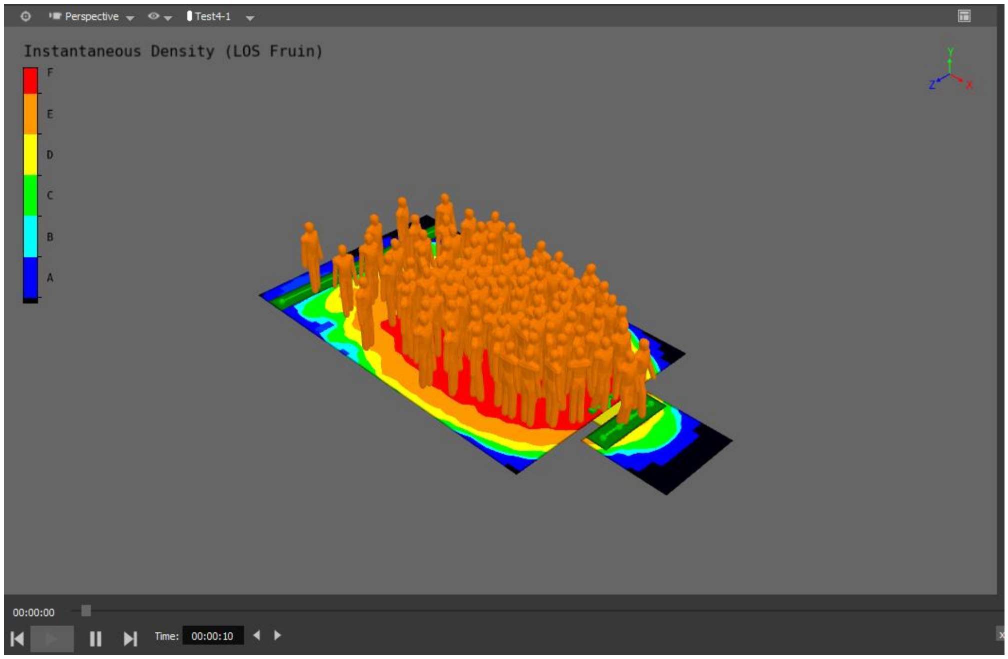

Figure 5: Mass Motion Level of Service Mapping Example

This mapping is useful in identifying areas of congestion during analysis. It is interesting to note that as body size is increased the map does not accommodate these changes (as it is based on the Fruin levels of service which have units in persons/m^2). The people in Figure 6 below have a diameter which is larger than Figure 5 above by 0.225m, and yet, with only small exceptions which are due to randomness within the model, the map shows contours similar to that of Figure 5. It can be noted that there is more space between individuals which is likely representative of the increased body size of the agent (though the body graphic remains the same). This makes the crowd appear more spread.

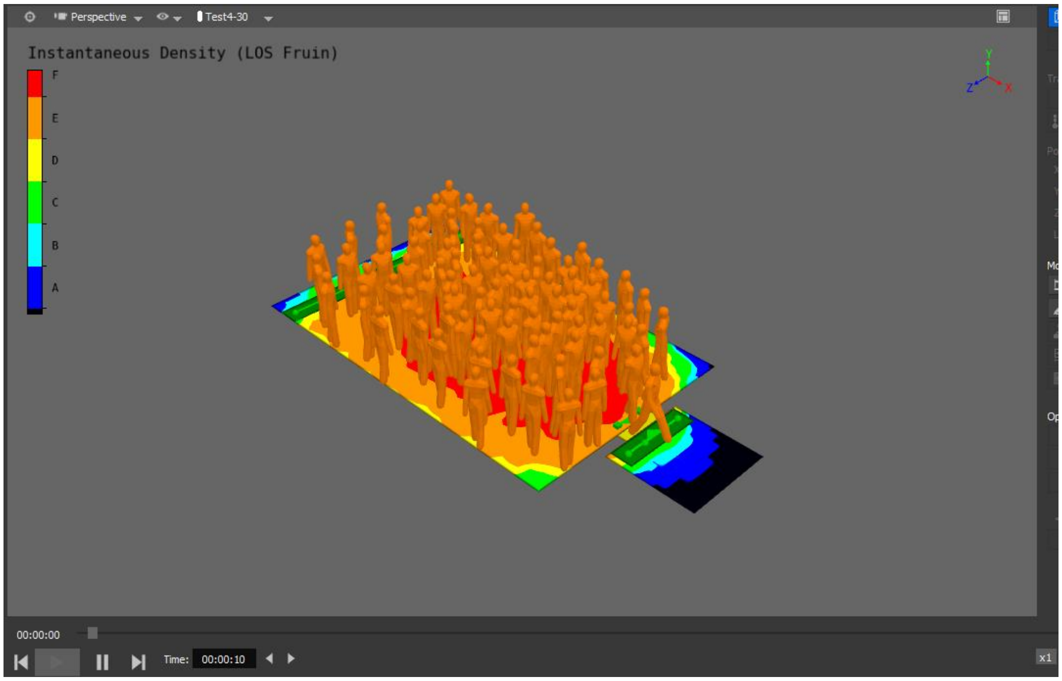

Figure 6: MassMotion Density Map with enlarged individuals

MassMotion is also able to create a randomness using a random seed within the simulations. If run with the same random seed the result should be the same. Testing with a change in random seed is done to create a distribution of egress times and to establish a mean. Changing the random seed of the simulation increases the entropy of the scenario by increasing randomness in the algorithm, which will result in a normal distribution of results about a mean. A simple test changing the random seed for Test 1 described in Chapter three was completed and it was found that the results observed without changing the random seed were nearly identical to the mean produced when the random seed was changed. Therefore, for simplicity of the test scenarios and for repeatability purposes the random seed was left as the default that was generated automatically for each scenario.

3.4.2: Pathfinder

The newest version of Pathfinder allows the user to select a mode which makes the simulations occupants to move at a maximum velocity that is dependent largely on the spacing of the surrounding occupants and an estimate of occupant density, a feature which is similar to the movements incorporated into MassMotion (Thunderhead Engineering). This density is based on the theories of Fruin shown in *Pedestrian Planning and Design* (1987). There are two choices of modes; “steering mode” or “SFPE” mode.

Steering mode effects the queuing behavior where individuals seek space in a queue instead of standing still and provides a more complex and natural human movement into the model by allowing agents to move in curved paths as well as to accelerate and decelerate. The SFPE mode utilizes straight line paths and constant speeds and is considered to fall more into the movement model parameters rather than the partial behavioral. When used in steering mode the model is deemed to be a partial behavioral model as it incorporates the ability for the user to create distributions for walking speeds, collision avoidance and queuing behaviors.

Pathfinder does not allow for many other human-like adjustments, for example, there is no option to create a ‘Right bias’ as there is in MassMotion. Allowing a bias incorporates a very often seen phenomena in which people will tend to pass others with a ‘bias’. In the case of North American populations individuals tend to bear right and pass others on their left. Generally, the lack of human like adjustments and behavior incorporation makes the testing run in Pathfinder less realistic when it comes to the observer prospective.

Pathfinder assumes a circular projected body area and represents a body as a cylindrical volume. The default setting in Pathfinder assumes a constant value for a shoulder width of 48.85 cm which closely aligns with what is presented by Predtechenskii and Milinskii. Body depth is not an option and therefore Pathfinder models body shape as a circular area rather than an ellipse. Similarly to MassMotion, the user is able to change the body size distribution in Pathfinder from constant to uniform, normal, or log-normal. Again, with reference to the body distributions discussed, the CDC data suggests the most likely scenarios are either normal or log-normal. In Pathfinder when the default distribution is changed from uniform to normal there is no standard deviation which is automatically assumed, instead it is set at 0.00 cm. If the user does not change this distribution the results will be the same as those which are constant. The default minimums and maximums also remain at 48.85 cm and would need to be altered to create an actual distribution. Also, interesting to note is that MassMotion does not change the agents 'avatar' size when the body size is adjusted. Pathfinder does allow the cylinders representing the agents to change size.

To correspond to the tests run in MassMotion a diameter is calculated for Pathfinder which would match the diameter (two times the radius) input into MassMotion. The default diameters (in MassMotion) are generous compared to the observations of researchers and the default setting of Pathfinder. The Pathfinder numbers will be manipulated to correspond with the MassMotion defaults as a baseline for testing.

Similar to the abilities of MassMotion, Pathfinder allows a user to view the output in a number of ways. One of the ways which is relevant to this work is by density mapping. The "map" once again shows contours which map the Fruin levels of service in the units of persons/m^2.

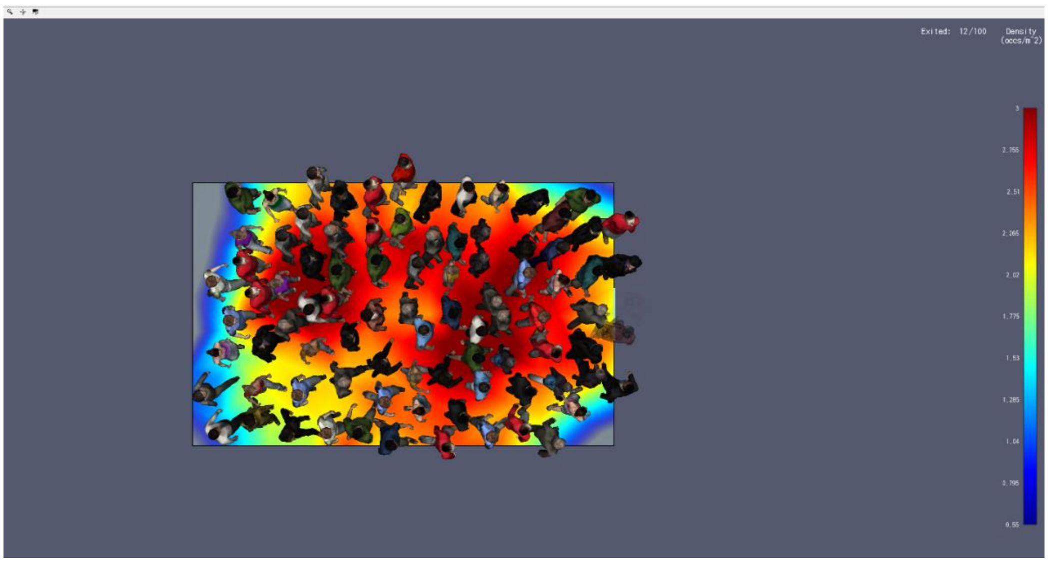

Figure 7: Pathfinder Density Mapping

The figure above shows the density mapping of the smallest body size during an iteration of one of the tests analyzed. Figure ___ below represents the largest iteration. Like MassMotion pathfinder uses the Fruin Levels of Service and so a large disparity between the maps would not be expected as body size increases.

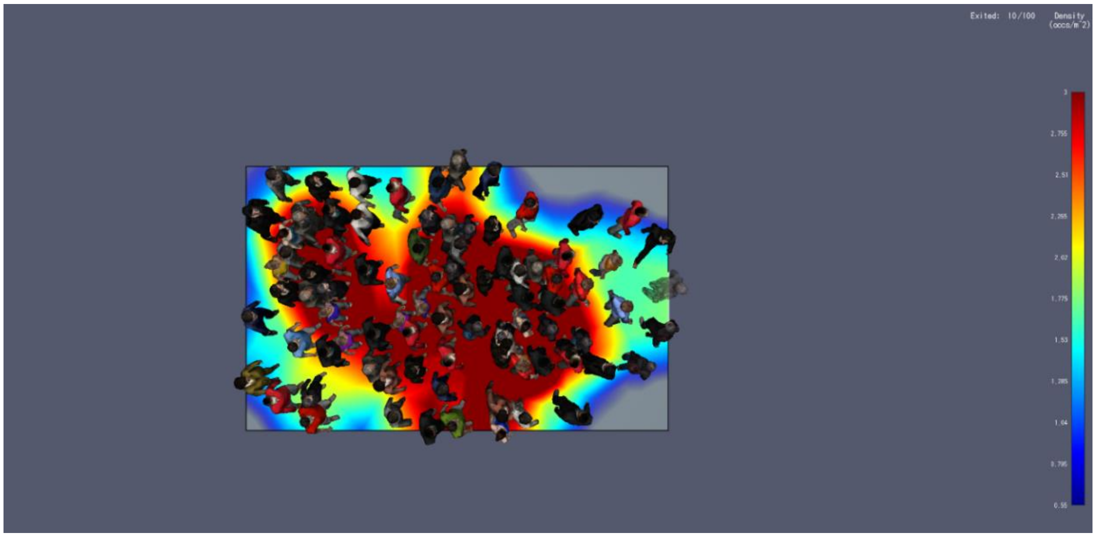

Figure 8: Pathfinder density mapping with enlarged individuals

It is significant to note that the increase in size of people yields error messages in Pathfinder. The error allows the user to select an option to “overlap occupants” “uniformly distribute as many occupants as possible” or “randomly distribute as many occupants as possible”. This phenomenon occurs in many of the tests which are prescribed by the IMO and NIST standards.

Chapter 4: Methodology

4.1: Design

This research was designed to quantify the percentage of time increase that could be expected as body size increases over certain intervals.

This research will utilize both the IMO Circular and the NIST Technical Note as the basis for the tests which will be conducted to look at the impact of body size. These tests incorporate a simple geometry and were selected because of the variety of components (i.e. Single Exits, Multiple Exits, Stairways, and Corridors). The population also varies in terms of the number of agents which are used in each one. Choosing simple geometry components gives the ability to begin to address the issue of size at a smaller scale and on a finer scale. Additionally, if testing using live test subjects the simple geometry scenarios would be easier to replicate than a complex scenario. They could even potentially be identified as a component of larger scale validation tests.

4.2: Software

MassMotion and Pathfinder were the software programs chosen for this research, and many of the features of each were described in Chapter 3. There are several reasons MassMotion and Pathfinder were selected as the testing software for this research. Since the design of the experiment utilizes guidance and suggestions from both the IMO and NIST, it was important that both software programs be verified to meet the guidance. Typically, the tests within the IMO requirements and NIST guidance are divided into two categories: component testing and qualitative testing. Component testing evaluates whether the structural components perform as intended. Since MassMotion and Pathfinder have successfully met the guidance of the component testing, it is an assurance that the components have been shown to behave in the manner suggested and will allow the testing to be concerned with body size while eliminating the potential that a given component does not perform correctly. Additionally, both have done validation cases (Rivers et al 2013, Thunderhead Engineering 2017). Additionally, both of the software programs allow for advanced analysis of the output using mapping and graphing methods as well as incorporating fundamental data collected in the fire protection field regarding movement, boundary layers, speeds, and densities. Both MassMotion and Pathfinder allow for changing of the body size, which is the most critical component of this project.

There are however, pertinent reasons why the two were chosen due to the ways in which they contrast. MassMotion is regarded as one of the more sophisticated software programs currently on the market and incorporates artificial intelligence and social forces capabilities (ARUP 2015). Pathfinder does not yet incorporate artificial intelligence.

4.2.1: Software settings

To isolate the impact that body size alone, all other factors will remain as the default settings included the models. This includes movement speeds, behavioral patterns, and size and dimensions of the design test components. For MassMotion the critical settings include the following: evacuate (journey type), no delay before movement, right bias, Fruin Commuter patterns and default walking speeds. In Pathfinder the mode was selected to be ‘steering’ mode to more closely align with both real world scenarios and the MassMotion model. The agent speed, collision avoidance and other details are all left at the defaults which appear as steering mode is selected. The body size is changed to a normal distribution, which generates default heights and width dimensions of the cylinders to be used for agent size. The height is left at the default setting while the body size diameters are changed according to the test parameters.

4.3: Test Design

The testing consists of two general features; body size and the geometry of the tests built. The following sections discuss details on the formulation and information used to create the structure used in the process of testing.

4.3.1: Body Size Design and Details

Combining the data which was accumulated by the CDC over the last 30 years and combining it with the historical fire protection literature data gives a guideline for developing testing parameters.

As stated in Chapter 2, one of the best ways of normalizing weight and height to get an idea of body size is using the BMI calculation from Chapter 1. Using the idea that over the last 30 or so years BMI has increased by a minimum of 16.5% a baseline of building some test parameters is started. Then, assuming that BMI is correlated directly to physical body size, and beginning with the MassMotion standard setting of 0.25 meters, an increase in body size based on the 16.5% which BMI has increased can be used to determine a body size which may be more representative of current day individual size. Using the percentage increases of BMI and assuming they correlate directly to body size can be used as a base to formulate inputs for body size in MassMotion and Pathfinder.

Initially the range of values which are used for mean sizes should range between 0.25 meters and 0.35 meters if they are based on the Fruin standard body size. MassMotion does establish 0.25 meters as a mean and so that will be the lowest mean considered. A 16% increase of 0.25 meters becomes 0.27 meters. At 0.35 meters a 16 percent increase yields a new radius value 0.41 meters.

Table 4: Radius values with corresponding 16% increase

Radius (m)	16.5% increase - Radius(m)
0.25	0.269
0.275	0.296
0.3	0.323
0.325	0.350
0.35	0.377
0.375	0.404
0.4	0.431
0.425	0.458

Table 4 is used to begin formulating body sizes to be input into the model. As previously stated 0.25-0.35 is the Fruin standard. Rather than stop at a value of 0.41 which would correspond to a 16% increase of the high end of the body size suggested by the literature the decision was made to surpass the 16% point so that data could be examined about what the potential impact would be if the body size of the population continues to grow. This was considered because the reported Fruin body size was based on research conducted in New York City commuters which tend to have significantly lower rates of obesity and overweight individuals as stated in Chapter 2 (CDC 2018, NYC.gov 2018). Going above the 16 % increase value which was observed as the mean also allows for some understanding of how a changing distribution, particularly a distribution with a right skew, may effect the evacuation times. As such the testing iterations incorporate a body size with a radius of up to 0.475 meters. This would indicate a total circular diameter of 0.95 meters.

The minimum suggested by MassMotion is 0.125, which is half the size of the mean. Though the average BMI has climbed there is no evidence that the lower end of the BMI is getting any lower and therefore the minimum for each test run will remain at 0.125.

Standard deviation is used to examine the effect of the changing shape of the distribution. The idea that the distribution shape could be shifting or changing is described in the early portions of this report and was addressed by creating standard deviations beyond the default settings which are suggested by MassMotion (Pathfinder does not generate a default standard deviation when a distribution is selected).

The goal within the creation of the test's was to separate variables and so each set of 6 tests runs the same intervals of maximum and minimum values while the standard deviation value remains at a set value (Test Numbers). The intervals are then repeated while the standard deviation changes (Test Set). This was done to allow for analysis of standard deviation changes and body size increase separately as well as together.

Table 5 shows the arrangement of each test and test set. There are 5 test sets which are each run 6 times with a constant standard deviation while changing the mean and maximum values. As established above the minimum value for body size stays constant throughout the testing. MassMotion values in the table are represented as meters of a radius, and Pathfinder is represented as cm for a diameter. These correspond to the model and the way in which they formulate the dimensions of the agents.

Table 5: MassMotion & Pathfinder Test Details

MassMotion						Pathfinder				
Test	Min (m)	Max (m)	Mean (m)	Std Dev (m)	Test Set	Test	Min (cm)	Max (cm)	Mean (cm)	Std Dev (cm)
1	0.125	0.35	0.25	0.0625	Set 1	1	25.00	70.00	50.00	12.50
2	0.125	0.375	0.275	0.0625		2	25.00	75.00	55.00	12.50
3	0.125	0.4	0.3	0.0625		3	25.00	80.00	60.00	12.50
4	0.125	0.425	0.325	0.0625		4	25.00	85.00	65.00	12.50
5	0.125	0.45	0.35	0.0625		5	25.00	90.00	70.00	12.50
6	0.125	0.475	0.375	0.0625		6	25.00	95.00	75.00	12.50
1	0.125	0.35	0.25	0.08	Set 2	1	25.00	70.00	50.00	16.00
2	0.125	0.375	0.275	0.08		2	25.00	75.00	55.00	16.00
3	0.125	0.4	0.3	0.08		3	25.00	80.00	60.00	16.00
4	0.125	0.425	0.325	0.08		4	25.00	85.00	65.00	16.00
5	0.125	0.45	0.35	0.08		5	25.00	90.00	70.00	16.00
6	0.125	0.475	0.375	0.08		6	25.00	95.00	75.00	16.00
1	0.125	0.35	0.25	0.09	Set 3	1	25.00	70.00	50.00	18.00
2	0.125	0.375	0.275	0.09		2	25.00	75.00	55.00	18.00
3	0.125	0.4	0.3	0.09		3	25.00	80.00	60.00	18.00
4	0.125	0.425	0.325	0.09		4	25.00	85.00	65.00	18.00
5	0.125	0.45	0.35	0.09		5	25.00	90.00	70.00	18.00
6	0.125	0.475	0.375	0.09		6	25.00	95.00	75.00	18.00
1	0.125	0.35	0.25	0.1	Set 4	1	25.00	70.00	50.00	20.00
2	0.125	0.375	0.275	0.1		2	25.00	75.00	55.00	20.00
3	0.125	0.4	0.3	0.1		3	25.00	80.00	60.00	20.00
4	0.125	0.425	0.325	0.1		4	25.00	85.00	65.00	20.00
5	0.125	0.45	0.35	0.1		5	25.00	90.00	70.00	20.00
6	0.125	0.475	0.375	0.1		6	25.00	95.00	75.00	20.00
1	0.125	0.35	0.25	0.11	Set 5	1	25.00	70.00	50.00	22.00
2	0.125	0.375	0.275	0.11		2	25.00	75.00	55.00	22.00
3	0.125	0.4	0.3	0.11		3	25.00	80.00	60.00	22.00
4	0.125	0.425	0.325	0.11		4	25.00	85.00	65.00	22.00
5	0.125	0.45	0.35	0.11		5	25.00	90.00	70.00	22.00
6	0.125	0.475	0.375	0.11		6	25.00	95.00	75.00	22.00

4.3.2: Geometric Design of Tests

The simplicity of a geometric design allows for a simplistic and detailed analysis. Therefore the tests which are used within this research are based on some of the tests seen in the IMO Circular, which are considered simple and indicative of evacuation of common components. The IMO Circular uses these simple scenarios to evaluate a models suitability for larger and more complex evacuation scenarios. Thus, since MassMotion and Pathfinder are both already verified for compliance with these standards (and further with NIST Tech Note 1822) these tests can be used to evaluate the impact of body size, eliminating the concern that the geometry may be influencing the software and output of results. Not all of the tests included in the guidance will be utilized, just those which give a sample of what the potential impact to evacuation times due to body size enlargement. A description of each of the tests follows.

4.3.2.1: Test A

This test is based on IMO test 4: Exit flow rate which states:

"100 persons (p) in a room of size 8 meter by 5 meter with a 1 meter exit located centrally on the 5 meter wall. The flow rate over the entire period should not exceed 1.33 persons/second." (IMO 2015)

Since both models have been verified to comply with the exit flow rate test, the purpose of this test is to examine the effect of an increase in body size in a very simplified test design scenario rather than for an examination of the flow rate through the doorway.

4.3.2.2: Tests B and C

These tests are based on IMO test 9: Exit flow: crowd dissipation from a large public room. The instructions for the test state:

> "Public room with four exits and 1,000 persons uniformly distributed in the room. Persons leave via the nearest exits. Choose a panel consisting of males 30-50 years old from table 3.4 in the appendix to the Guidelines for the advanced evacuation analysis of new and existing ships with instant response time and distribute the walking speeds over a population of 1,000 persons.
>
> Step 1: Record the time the last person leaves the room.
>
> Step 2: Close doors 1 and 2 and repeat step 1."

Test B will be the completion of Step 1 and will report on the results of the case where all the doors are open. Test C will therefore be the completion of Step 2 and will report on the space where the exit flow is changed with the closing of the two doors as described. The geometry is shown below and is also extracted from the IMO standard. Figure 10 below shows the geometry and the dimensions of the room for Tests B and C.

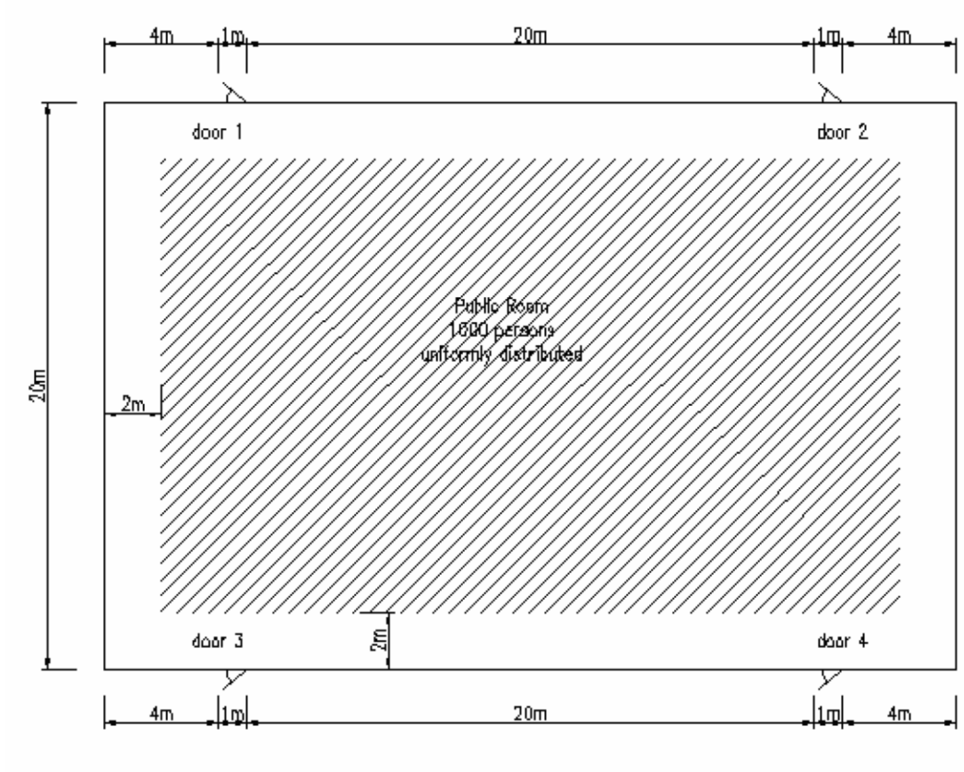

Figure 9: Exit Flow from a Large Public Space (IMO Circ. 1533 2015)

4.3.2.3: Test D

This test is based on IMO Test 11. The test description from the IMO states:

"Construct a room connected to a stair via a corridor as shown in figure 4 populated as indicated with a panel consisting of males 30-50 years old from table 3.4 in the appendix to the Guidelines for the advanced evacuation analysis of new and existing ships with instant response time and distribute the walking speeds over a population of 150 persons. The expected result is that congestion appears at the exit from the room, which produces a steady flow in the corridor with the formation of congestion at the base of the stairs."

Figure 10 shows the layout and dimensions of Test D.

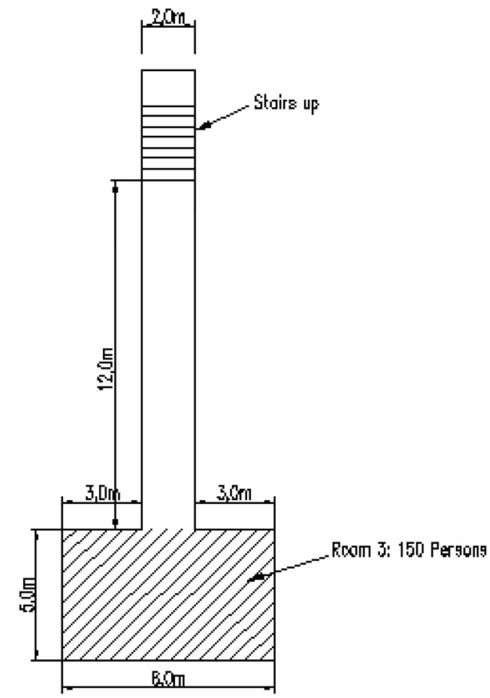

Figure 10: Diagram of Test D Layout (IMO Circ. 1533 2016)

4.3.2.4: Test E

This test is based on IMO Test 12 which states:

"The software should be tested for a Corridor without any obstructions. It should be demonstrated that the flow of persons in the corridor is generally smaller at very high population densities compared with that at moderate densities."

For this test the agents were allocated throughout the corridor with an exit on one end. The test is populated with100 Agents and the corridor is 15 meters by 1.12 meters.

Table 9 shows the results in seconds, once again with MassMotion being in the first column and Pathfinder in the second.

4.3.2.5: Test F

This is not a test found in the IMO Circular or the NIST Note. It is however, important to understand how merging flows may appear as they are extremely common in evacuation and flow scenarios.

50 people travel from each end of two corridors (100 persons total) which merge at a 90-degree angle with a single corridor. The exit is at the termination of the single corridor.

4.4: Randomness Testing

MassMotion allows for multiple iterations of the same test to be run consecutively without editing the inputs. If the test is run with the exact same inputs and the generated random seed established during the geometry design process the expectation is that the results will be consistent across the number of tests run. When the random seed is adjusted it will introduce randomness into the algorithm and would be expected to produce a distribution of results.

This feature was tested in Test A to establish an estimation for accuracy of the reported results. Each of the individual tests was run 10 times with a random seed value of 10. The total number of tests run was 300 (10 each of 30 test sizes). In all cases the median result was within the area of 2.5% of what the model suggested as a result without changing the random seed.

Test A randomness testing for test 1 of test set 1 is shown below. The result of the randomness testing shows an average evacuation time of 72 seconds, a value around 2% more than what is reported in the results section of a single test.

Table 6: Example of Results from Randomness Testing

1	1	74
	2	72
	3	72
	4	72
	5	73
	6	76
	7	71
	8	71
	9	73
	10	73
	Mean	72

Due to the minimal variations observed in the results of Test A when the randomness factor was changed the choice was made to report a single answer understanding that what is reported is generally within 2% of the reported single test.

4.5: Procedure

Each Test set (based on a standard deviation) will be run through 6 different body sizes. The first time will utilize the body size most closely aligned with the standard body size incorporated into both MassMotion and Pathfinder which is based on the work of

Fruin. The largest body size goes well beyond projected body size, which would be approximately 16% larger than what Fruin suggested if the weight and BMI increase is assumed to correspond directly to a body size increase. As Fruin observed people are likely to be carrying objects and are rarely expected to be moving and evacuating without any personal items (1987). Using 6 different body sizes and 5 different test sets results in 30 simulation runs which are completed for each geometry.

Hand calculations were completed using the hydraulic model as another comparison and estimation source beyond using the software. The hydraulic model is one of the earliest standing methods of predicting evacuation times and is used primarily for reference purposes in this research.

4.6 Data Collection:

From the software programs data is able to be extrapolated for further analysis. MassMotion has features which show data such as exit time of each agent in tabular form. Pathfinder allows the user to see the room population in graphic form which allows the user to see the time at which the full population has exited the room.

4.7 Method of Analysis:

There are a number of things which can be looked at when analyzing the data. The test with the smallest size can be compared to the largest size to get a percentage increase of time which corresponds to a body size increase that is 0.225 meters larger than the first test.

First, an evaluation can be made regarding the of the impact of the change in standard deviation. This is completed by observing the variability between test sets as each tests a different standard deviation. This would potentially indicate the changing dynamics of a distribution on the effects of time.

Finally, and perhaps most importantly, the results can be examined from the perspective of a time increase per size increase interval per person. This is likely the best way to estimate from scenario to scenario and to compare between test geometries as each has a different number of people in addition to a change in geometry. Examining this value could show trends in an approximate time and could be translated into a useful numerical factor to consider basing new scenarios around.

Chapter 5: Test Results

The contents of this chapter display the test results for the test geometries (A-F), as well as each test run. The results are shown graphically in this section and are contained in tabular form in Appendix A. An analysis of the results which are displayed occurs in the following chapter (Chapter 6). The hand calculation results are also contained below for comparison. The calculation methods used for each are contained in Appendix B.

5.1: Test A

The results of Test A appear graphically below in Figure 9. In all of the Pathfinder simulations for this test the agents took longer to reach the exit then in MassMotion. The results of the tests in Pathfinder also had a greater rate of change than what was observed in the comparable test results of MassMotion. In the results for MassMotion the times were lower as was the rate of change (difference between) each sequential test.

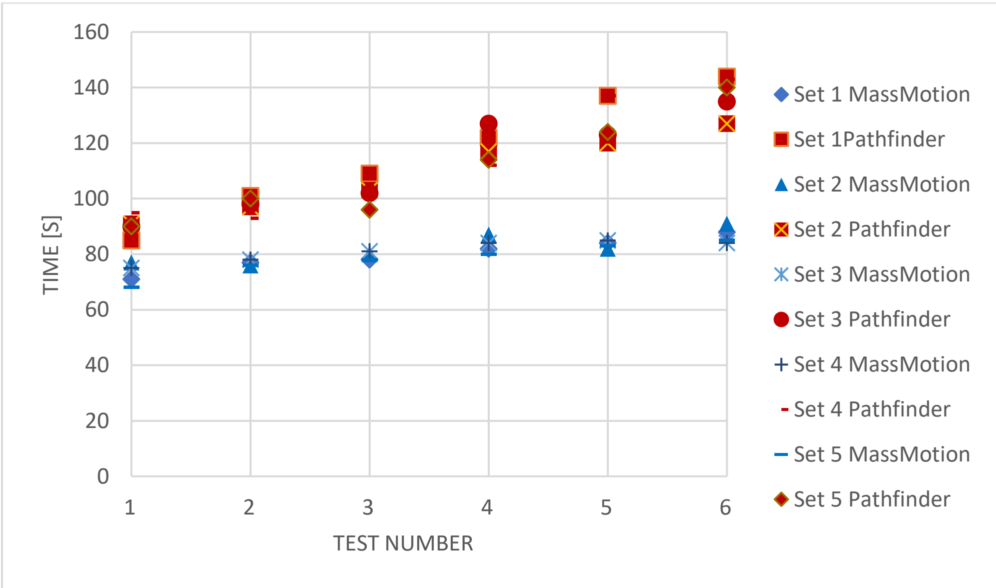

Figure 11: Graphic Representation of Results, Test A

The hand calculation for test A yields a result of 128 Seconds (2 minutes 8 seconds) which is most similar to that of pathfinder at a larger size of agent. At the Fruin standard size both MassMotion and Pathfinder yield results which are lower than the hand calculations. Details of the hand calculation process are contained in Appendix B.

5.2: Tests B & C

Figures 12 and 13 below are graphic representations of the MassMotion results and the Pathfinder results of Tests B and C. These graphs show something of note. The IMO Circular suggests that when two of the doors are closed the time for evacuation should double (IMO Circ. 1533 2015). Looking at the figures above this appears true in Pathfinder, but MassMotion does not respond in a similar fashion. The time initially is close to double but does not grow at a rate similar to when the doors are all open. At the larger body sizes the MassMotion results with all four doors open show response times only marginally lower than with 2 of the doors closed.

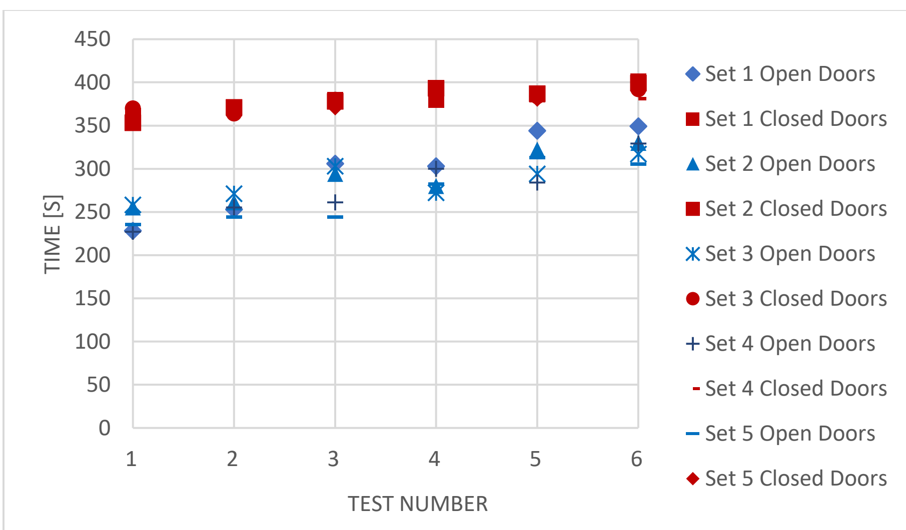

Figure 12: MassMotion Results Tests B & C

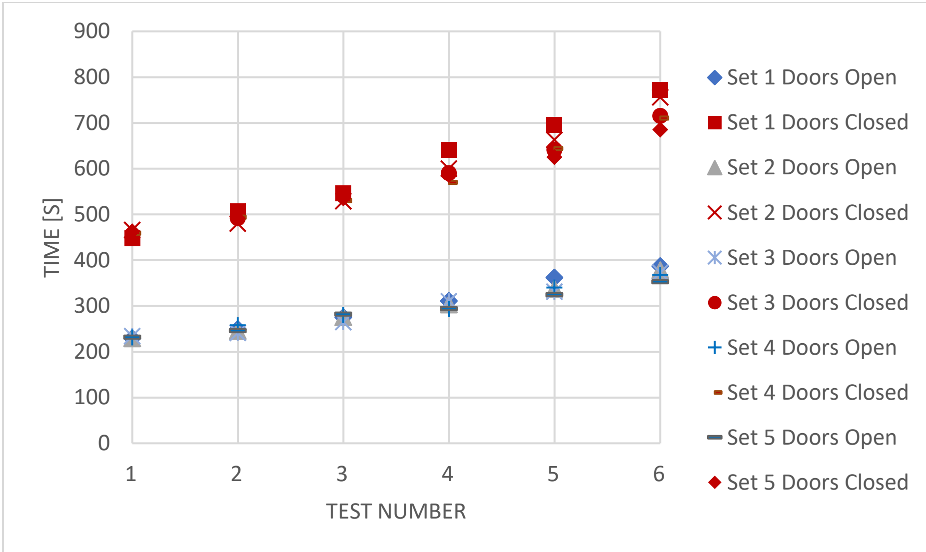

Figure 13: Pathfinder Results Tests B & C

Figures 12 and 13 show something of note. The IMO Circular suggests that when two of the doors are closed the time for evacuation should double (IMO Circ. 1533 2015). Looking at the figures above this appears true in Pathfinder, but MassMotion does not respond in a similar fashion. The time initially is close to double but does not grow at a rate similar to when the doors are all open. At the larger body sizes the MassMotion results with all four doors open show response times only marginally lower than with 2 of the doors closed.

Figures 14 and 15 show the graphic results of each test with MassMotion and Pathfinder. As can be seen in Figure 14, for Test B MassMotion and Pathfinder closely aligned on the time to evacuation for teach test set. In Figure 15 the Test C results show something different with a greater variance between MassMotion and Pathfinder just in restricting the number of doors available for egress.

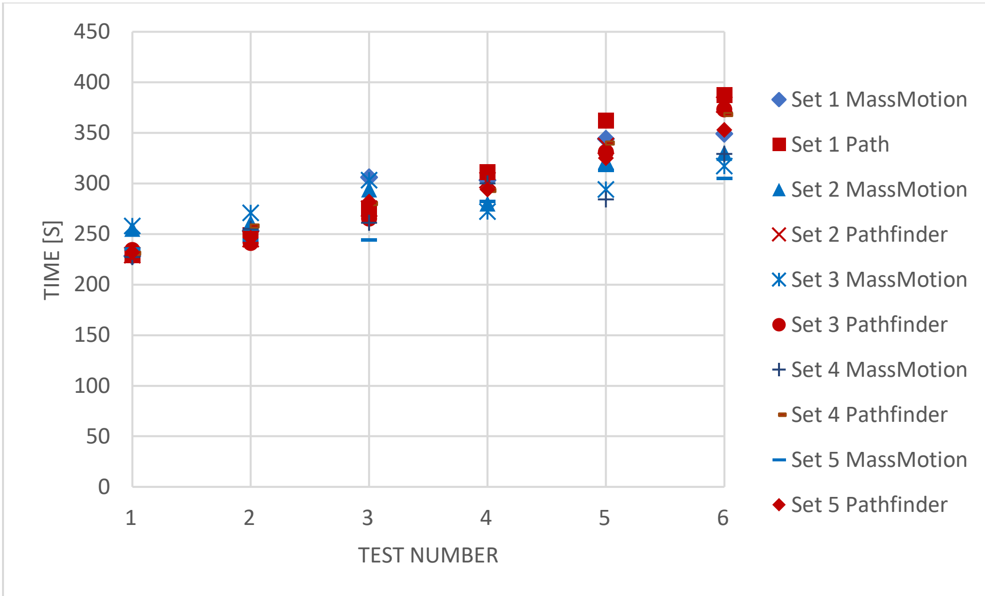

Figure 14: Graphic Results, Test B, All Doors Open

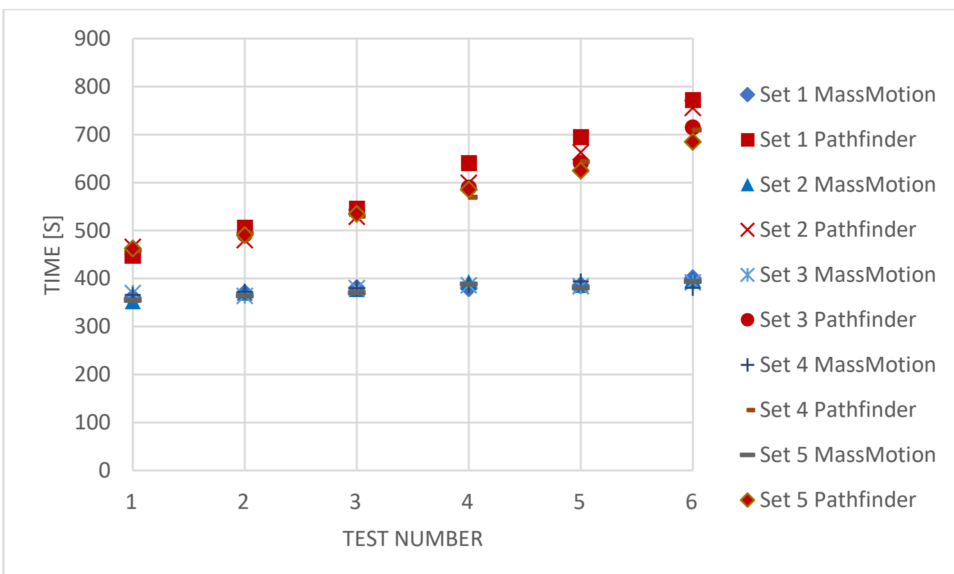

Figure 15: Graphic Results, Test C, 2 doors closed

Comparing Figure 14 and Figure 15 is interesting. As Figure 15 reinforces MassMotion does not perform as expected. The expectation, particularly with the knowledge of the results of Test B would indicate that Test C should also show results between MassMotion and Pathfinder that closely agree on time.

Overall the results of Test B (with all doors open) indicate an increase of time in Pathfinder of 23.4 seconds per 0.025 meter of body size increase and in MassMotion of 14.2 seconds per 0.025 meter of body increase. Results of Test C (with 2 of the doors closed) indicate an increase in Pathfinder of 45.1 seconds per 0.025 meter of body size increase and in MassMotion of 5.4 Seconds per 0.025 meters of body size increase. It should be noted that the way MassMotion performs with 2 of the doors this is an unexpected result. This could be caused by a number of things. Initially the thoughts could indicate that the program does not respond correctly to the increase in body size, however, in all the other tests the rate of increase, though generally lower than pathfinder, shows an impact of body size. The other possibility, and perhaps more likely scenario, is that the Artificial Intelligence portion of MassMotion plays a role. If the occupants know the exits are restricted that could cause a force that would initiate a higher speed of movement toward or through an exit. Pathfinder performs as predicted by both the IMO and hand calculation predictions with nearly a double in the total time to evacuation.

The completed hand calculation for Test B, the test in which all of the doors are open in the room yields a result of 267 seconds (4 minutes 27 seconds). Test C, in which 2 of the doors are closed, yields a hand calculation time of 554 seconds (9 minutes 14 seconds).

5.3: Test D

MassMotion and Pathfinder closely agree during Test D, which can be seen in Figure 16 Below. MassMotion indicates a rate of increase of 3.7 Seconds per 0.025 meter of body size increase. Pathfinder indicates a rate of just over 5 seconds per 0.025 meter of body size increase.

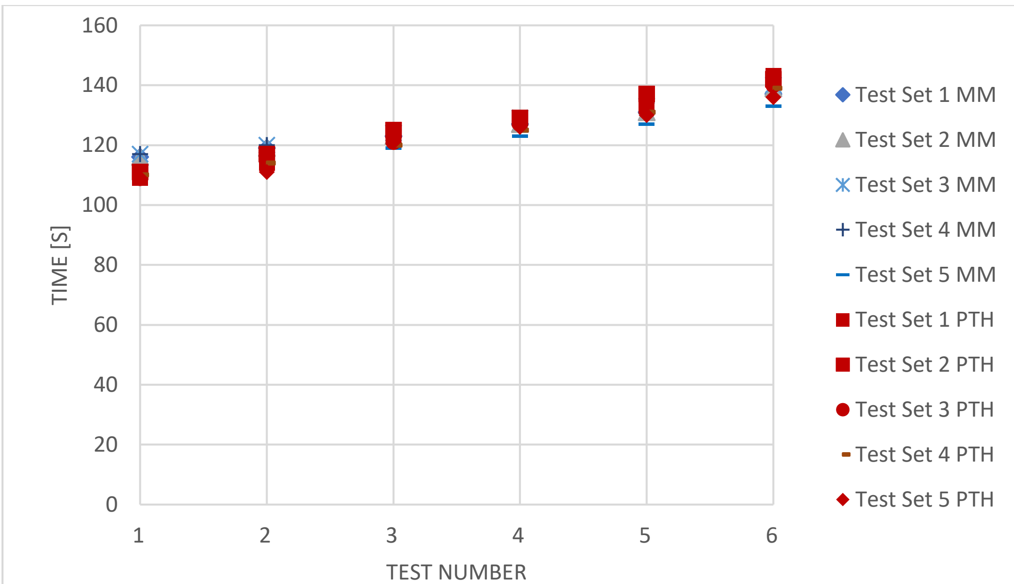

Figure 16: Graphic Results of Test D

Completing the evacuation calculation for Test D by hand yields a result of 116 seconds (1 minute 56 seconds) this in in line with the results obtained in the early tests (smaller body size) iterations of the computer simulations.

5.4: Test E

Figure 17 shows the results of Test E graphically. MassMotion indicates a rate of increase of 2.8 Seconds per 0.025 meter of body size increase. Pathfinder indicates a rate of 5.5 seconds per 0.025 meter of body size increase. For this test Pathfinder consistently shows times which are higher than MassMotion, but the rates of change (slopes) of each of the lines is similar to many of the other tests.

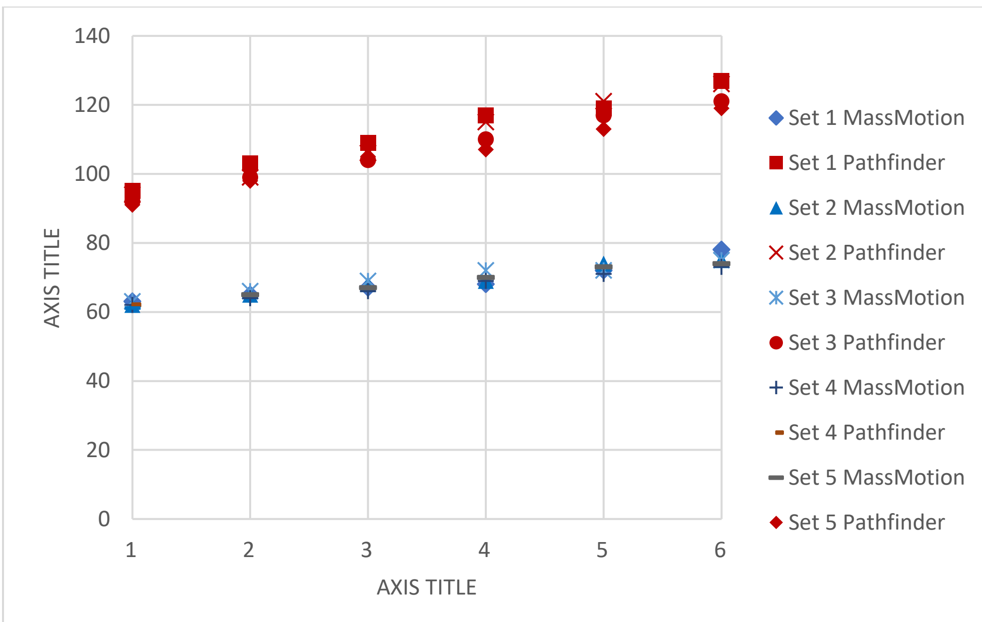

Figure 17: Graphic Results of Test E

Completing the hand calculation for Test E yields a result of 107 Seconds (1 minute 47 seconds). As indicated above MassMotion indicates results nearly 40 seconds faster. Pathfinder more closely aligns with the hand calculation.

5.5: Test F

The results of Test F are seen in Figure 18 below. Once again the results of Pathfinder are slightly higher than those of MassMotion throughout all the tests. The results of this test indicate an average increase of 3.3 seconds per 0.025 meter of body increase on the MassMotion simulation and an average of 6.9 seconds per 0.025 meters of body increase for the Pathfinder simulations. These rates of change are in line with what has been seen on some of the other test geometries.

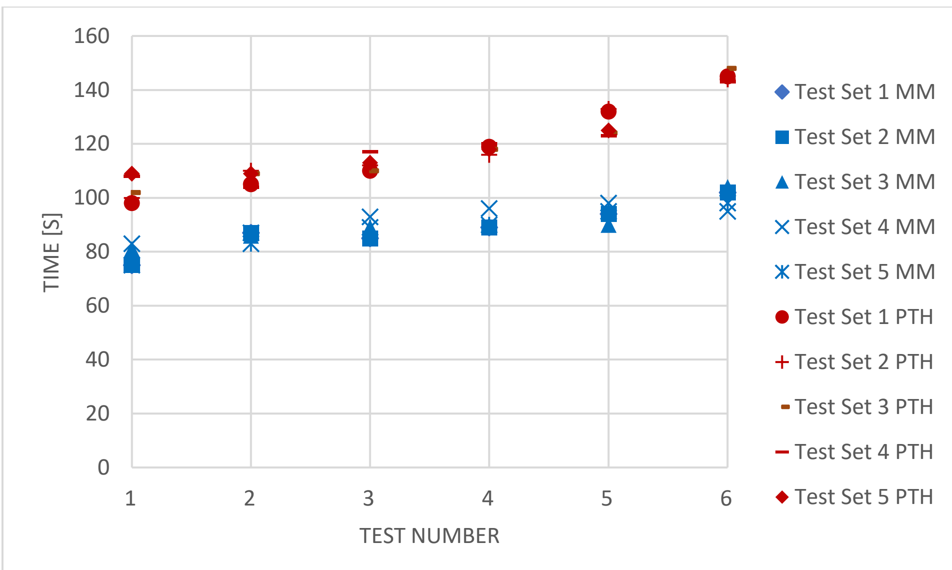

Figure 18: Graphic Results of Test F

Hand calculation results for Test F indicate that the total time to evacuation is 112 Seconds. Similar to the results of the other hand calculations this falls in the mid-size region (around test set 2-3) of the Pathfinder results.

Chapter 6: Analysis

6.1: A Further analysis of density

NIST and the IMO note often use a prescribed number of persons in a certain area for testing. A more in-depth review of this topic can be conducted to have a better understanding of density and the different ways it can be used and analyzed.

Using the three formulas presented in the literature provides different expressions of densities which may be applied into the regulatory framework. The three formulas are presented as Equations 3, 4, and 5 in Chapter 2. The majority of the work done within pedestrian dynamics and evacuations refers to densities in persons/m^2 or m^2/person (the result of equations 3 and 4). These units are also used in codes for determining capacities of spaces. However, it is important to consider what happens if people get larger but the capacities remain the same. The only density equation which takes this into account is Equation 5. Below is an examination of a simple example where the different densities can be calculated and see where a change in body size could affect the density of a population.

As an example, consider Test scenario A presented in Chapter 4. The room size is 5 meters by 8 meters (40 Square meters) and holds 100 persons.

Utilizing Equation 3 would give a density of 2.5 persons/m^2, Equation 4 a density of 0.4 m^2/person, and Equation 5 (using a fixed human radius of 0.25m and circular projection) gives a density of 0.49 m^2/m^2. If the size of a person increased the first two equations would result in the same densities as before. However, the density represented by Equation 5 would change. With a radius of 0.27 meters the horizontal projection of the area of a person becomes 0.229 m^2 which corresponds to a density value of 0.57 m^2/m^2. Further increasing the radius to 0.30 meters (area of 0.2827 m^2) the density becomes 0.73 m^2/m^2.

As discussed in Chapter 1 the average body weight has increased over 16.5% since the 1960's. Using Equations 3 and 4 to calculate density would show no change in the density calculated. Using the Equation 5 the density would change. With a 16% increase in body size the density (using Equation 5) would rise from a value of 0.49 to 0.57 m^2/m^2 as calculated in the example above. The examination of this measurement of density was done in the work of Predtechenskii and Milinskii. Their observations predict a slowing in the speed of movement as the nondimensionalized density moves from 0.49 to 0.57 and above. On a horizontal path they predict movement at a density of 0.49 as about 28 meters/min (maximum) and at 0.57 of 0.433 m/s (26 meters/minute), a slowing of approximately 7%.

At the values of density stated above (0.49 and 0.57 m^2/m^2) and converting the observed speeds by Predtechenskii and Milinskii, maximum values of horizontal travel speeds of between 0.466 and 0.433 m/s are obtained. Comparing that with the calculations using Equation 6 (Gwynne and Rosenbaum 2016) and a density in persons/m^2 (2.5), a value of 0.469 m/s is obtained. These values align well with the prediction of maximum speeds by Predtechenskii and Milinskii which are shown in Figure 19.

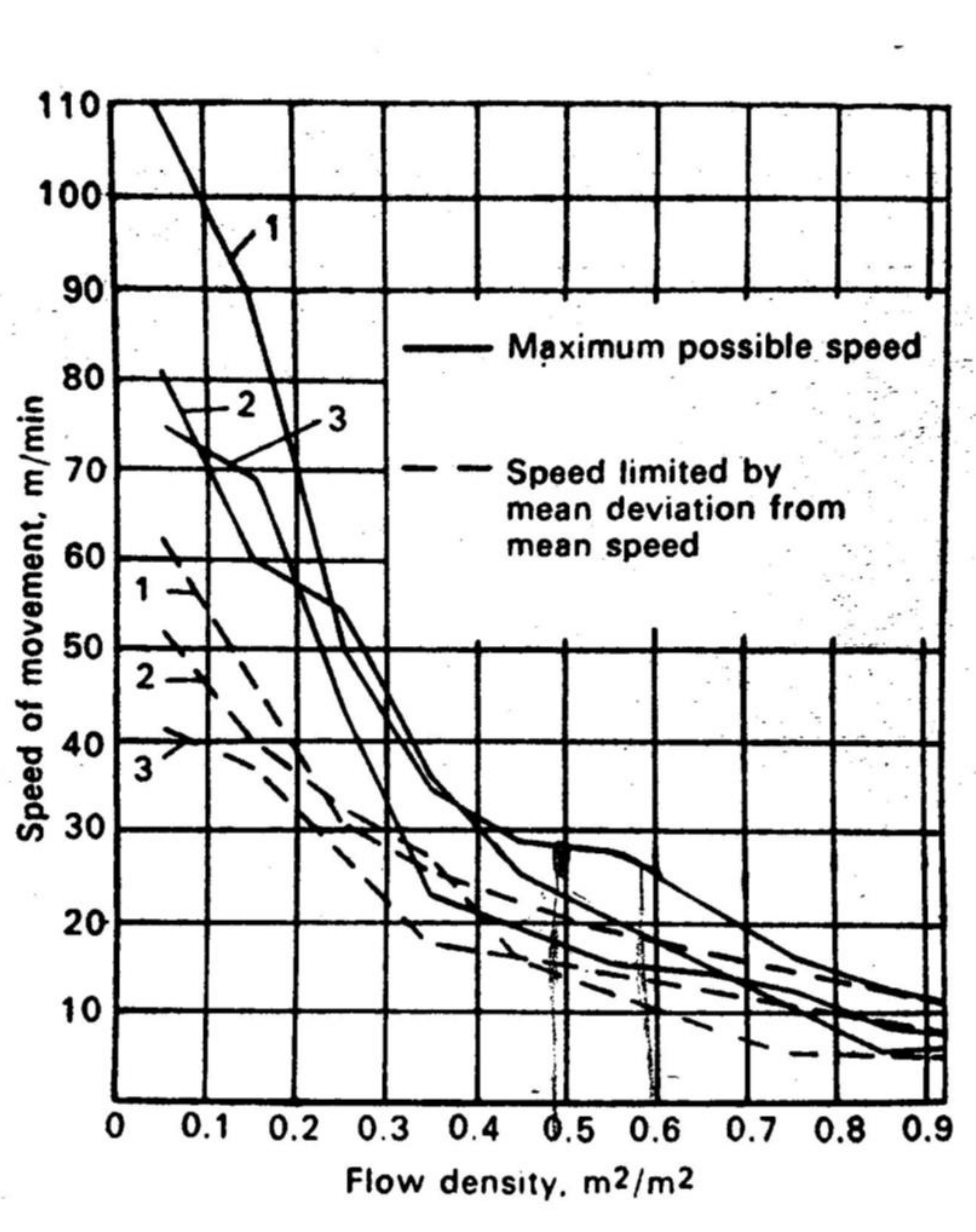

Figure 19: Maximum speed of movement with respect to flow density

(Predtechenskii and Milinskii 1987)

It is more likely that the speeds are lower (as the above is suggested as a maximum) and would range from approximately 0.36 m/s (21.8 m/min) at 0.49 m^2/m^2 to

0.33 m/s (20.26 m/minute) at 0.57 m^2/m^2 as shown in Figure 20 below. Comparing the speed values calculated in the SFPE Handbook method 0.469 m/s (28.02 m/min) with those suggested as average speeds observed by Predtechenskii and Miliniskii shown in the figure below the speed would be about 22% slower using the Predtechenskii and Milinskii data than if the SFPE Handbook is used.

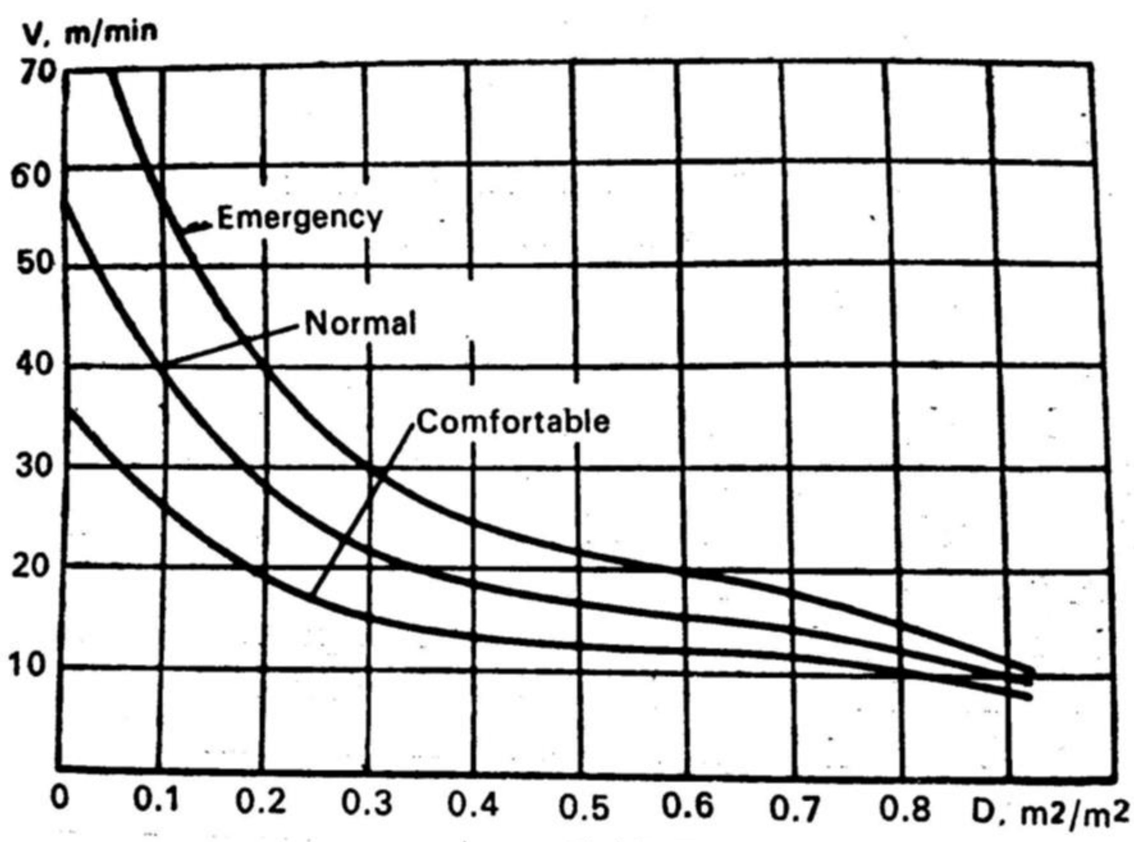

Figure 20: Speed of movement for horizontal paths, stairs, and openings as a function of density (Predtechenskii and Milinskii 1978)

This once again reinforces the need for an examination on whether or not taking body size and dimensions into account is worthwhile when looking into evacuations. A

22% difference in speed for a building population which remains the same could indicate as much as a 2.2 minute difference in a 10 minute evacuation. Though buildings are typically designed with safety margins, depending on how tight the safety margins are 22% is not an irrelevant amount of time, and effort should be made to consider the impact of the change in density when which is not dependent on the size of an individual.

Capacities of buildings are often listed based on the number of persons per a given area depending on the use. Codes also establish minimum widths based on the number of persons in a space (Bukowski, 2009). Because people have gotten larger these widths may no longer be optimized for use, and those dimensions may be altering the density (as calculated by Equation 5) in ways which may slow the flow of people during movement without even considering human behavior and the effects that increased body size may have on individual movement and health.

6.2: General Analysis

Both MassMotion and Pathfinder exhibit changes in all the egress scenarios test when the agent size is changed. This indicates that the models are able to make predications based on a changed physical size of an individual. How closely the predictions align with a real scenario would need to be verified utilizing a real evacuation data. In every test completed, Pathfinder predicted times that were a longer duration than MassMotion. Hand calculations analyzed using the SFPE Method align most closely with the predicted times by Pathfinder. Table 11 displays values which are important for analysis to understand the impact an increased body size could have on basic evacuation scenarios.

Table 7: Analysis of Test Results

	Test A	Test B	Test C	Test D	Test E	Test F
Total Persons in scenario	40	1000	1000	150	100	100
Max Time Diff (smallest to largest) MassMotion	23	128	46	24	17	29
Max Time Diff (smallest to largest) Pathfinder	59	158	324	34	33	53
Seconds per 0.025 m increase per person MassMotion	0.096	0.021	0.008	0.027	0.028	0.048
Seconds per 0.025 m increase per person Pathfinder	0.246	0.026	0.054	0.038	0.055	0.088
Percentage of time increased (smallest to largest body size) MassMotion	32.4	56.4	12.7	21.2	27.4	38.7
Percentage of time increased (smallest to largest body size) Pathfinder	69.4	69.0	72.3	31.2	36.3	54.1

The rate of increase of time per person per interval (0.025 meter increase) is low; generally being in the range of 0.05 seconds per person per 0.025m of body size increase. This shows that the impact that a body size has on evacuation scenarios depends greatly on the complexity of the evacuation geometry and distance to exit as well as the number of occupants in a scenario.

As Table 11 above indicates there are a few results which are somewhat unexpected. First, Pathfinder shows a significantly larger increase in time for Test A than would be expected given the other data points from the subsequent tests. MassMotion in Test C (the closed-door test) does not show results that would be expected as described previous in the Testing section. A graphic analysis of the results are below in Figure 21.

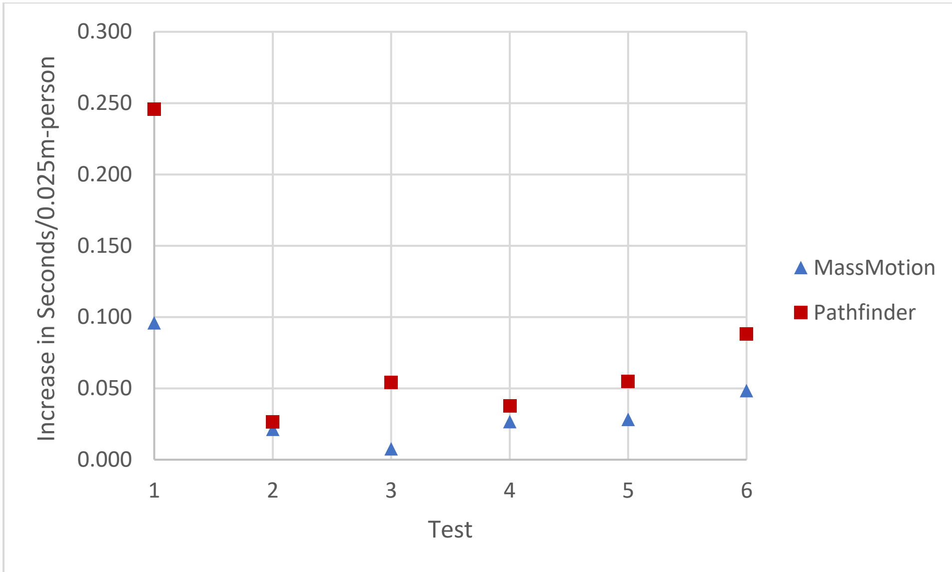

Figure 21: Graph, Time Increase (per 0.025m per person)

It is important to note that though there is some variation between the controlling elements and the test geometry, in all cases an increase in body size led to an increase in evacuation time. The extent of the increase of time was based on the model used (MassMotion vs. Pathfinder) and the geometry. This indicates that an expected outcome or increase of time might not be simple to predict as the increase in time would be dependent on both the size and demographics of the occupants as well as the building size, total occupancy, geometry and components. Table 12 below highlights the percentage increase in time which was obtained during the testing of each scenario. The range is large, with values between 12.7% and 72%. However, the values provide insight into the average increase each model would predict in a given scenario and indicates that overall, with an increase in body size an increase in evacuation time would be expected.

Table 8: Percentage increase in time (with a 0.225m increase in body size)

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
MassMotion	32.4	56.4	12.7	21.2	27.4	38.7
Pathfinder	69.4	69.0	72.3	31.2	36.3	54.1

Additionally, it can be noted that the body sizes utilized in this research were based on data collected regarding the American rates of overweight and obese populations. Americans are indicated to have some of the highest rates obesity and overweight populations. Though those body sizes are not indicative of world populations it is likely that the results and estimates based on an American body size growth would provide an additional safety factor based on the fact that the American population has higher rates of BMI's which fall into the overweight and obese categories. Figure 22 illustrates that the average BMI in the American population is higher than those of other developed nations.

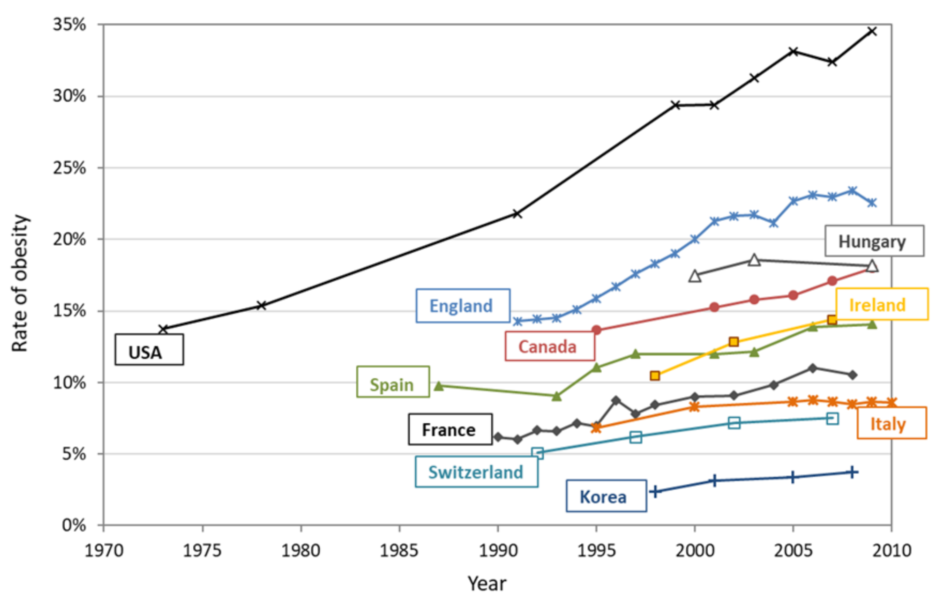

Figure 22: Obesity Rates in OCED countries (OECD 2012)

The results from the testing as discussed in this section show that as body size increases evacuation times also increase, indicating that the larger the people the longer the evacuation times. Incorporating these body sizes into the models would yield results which could show times of longer duration than may be applicable in other countries but could be assumed to increase the margin of safety for other populations.

Chapter 7: Uncertainty

Any time models are utilized there is inherently some uncertainty. This research has aimed at minimizing the variation of uncertainty in the models utilized (MassMotion and Pathfinder) outside of the variation of what is being tested i.e. body size. There are inherent uncertainties in any model, described often as intrinsic uncertainty which relates to those assumptions which are built into a model and cannot be varied.

Input uncertainties other than those which are changed to reflect the size changes of the physical bodies. No changes have been made to the default settings of the models beyond the body size. All boundary layers, walking speeds, and behaviors have been left as the default settings come in the software. These defaults have been based most often on a thorough review of the fire protection literature. By leaving these at the default settings the uncertainty between sets is minimized and the component and agents are truly what is being tested.

The hand calculations for the hydraulic style models also generate uncertainties. There are a lot of assumptions which are made when completing a first order hydraulic model. In the calculations above it is assumed that the first person is immediately on the path to flow out, which in some cases means assuming it takes zero seconds for them to reach the controlling element. In most hydraulic calculations delays are not taken into account unless otherwise prescribed, nor are other behaviors which may influence the ability of a person to move toward an exit. This indicates that most evacuation times will be longer than the hydraulic model predicts. (Gwynne and Rosenbaum 2016)

MassMotion has ways to test for uncertainties and develop an approach to generating a confidence level. When a scenario is designed MassMotion generates a prescribed random seed value. This value is able to be edited by the user. The test is also able to be run multiple times without the user having to manually start each test. Running the test a certain number of times with a specified seed should yield a distribution of outcomes. The mean of these values could then be used as a best estimate of the true time (particularly for evacuation scenarios). This was tested on the most basic test (Exit Flow) and discussed in the section which addresses the workings of MassMotion in Chapter 3. A distribution of values was obtained and the means closely aligned (less than 1% difference) with the values presented in the Testing results.

MassMotion has been, and continues to be, validated through the use of real world test scenarios. This has shown that MassMotion test results are within 10% of the time a real evacuation (Rivers et al. 2014). However, it is still critical to note that there is still an issue with certain aspects of the validation cases which may not make it applicable to all applications. In all of the MassMotion cases validated by Rivers, the tests were completed in major metropolitan areas where the persons are more likely to fall within the normal BMI distributions rather than the overweight and obese categories. The personnel were also familiar with the building structure and the structures were not at full operational capacity.

Chapter 8: Limitations and Areas for Additional research

8.1: MassMotion and Pathfinder

Software limitations where body areas are reflected as circles rather than ellipses may be inaccurate. While the horizontal projection of body size is generally agreed upon and estimated as an ellipse, software designers tend to use a circular projection because ellipses are difficult to model computationally (Dabney 2018; Zheng and Palffy-Muhoray, 2007).

Utilizing the area of a circle is likely to have impacts in the resulting time of the evacuation. For example, an ellipse has a wider with (when representing a human) than it does depth. Reducing this width and increasing the depth could potentially indicate that more agents could fit side by side than in actual cases because a portion of the width has been incorporated into the depth. Though the areas are the same the construction is not. A 12 by 12 meter room has an area of 144 square meters, as does a 16 by 9 meter room. The geometry is different and is not necessarily comparable. Since the models incorporate sizes based on the provided ellipse it would be advisable to examine the impact, if any, that modeling as a circle has compared to the modeling of an ellipse.

8.2: Further Research in Population Demographics

Pauls, Fruin, and Zappan stated in 2005 that there is a need for additional research on the effect of increased body size on movement during evacuation. This could (and should) include gathering demographic and physical data of people during evacuation scenarios to be used for the validation of models. Fruin suggested that shoulder width was the largest influencer of movement restrictions, now with a growing obesity rate, a shift to waist circumference might be justified as the dominating physical body characteristic for movement.

Without validation sets it is impossible to assess whether the software accurately predicts the movement of individuals correctly as body size increases. Little data can be found on the correlation of weight and BMI to actual physical body size, therefore it had to be assumed for the purposes of this investigation, that a 16% increase in weight or BMI would correlate to a 16% increase in physical size. Finding a correlation between standardized BMI and physical body size as well as an examination of weight distribution and dominating physical factors could allow for more accuracy with input data into models. One of the ways in which in which BMI could be simply correlated to a physical body size is through future reporting and investigation of data such as waist circumference and shoulder width.

The analysis of CDC data as well as the potential for impacts on increasing evacuation times also suggest that some of the baseline assumptions which are made and incorporated into evacuation models could be updated to reflect the incorporation of a more current body size. The literature review is overwhelmingly in agreement that body size is an important and critical feature of movement and that the standard body size which is incorporated into the software models is outdated and inaccurate for the majority of the U.S. Population.

When it comes to being able to predict possible impacts of the changes of physiology of individuals, it would be helpful to validate the simple scenarios with real life cases to address a changing demographic. Though the models have the ability to simulate some mobility impairment and address physical size as a factor in egress there are such a multitude of factors which go into evacuation dynamics (Rosenbaum and Boyce 2016). Additionally, though there are thoughts and some initial investigation into fatigue rates there could be further work which corresponds or examines fatigue rates with larger size Determining at what point an individual may show signs of fatigue as a function of body size would likely be a difficult endeavor as there are many factors to fatigue (Ronchi 2013)

Additionally, it needs to be mentioned that this study does not include analysis into the role that an increase in body mass has in diseases which may contribute to physical disabilities. Diabetes, heart disease, stroke and cancer are all diseases which are known to be strongly correlated to obesity (CDC 2018). These diseases also have potential mobility issues. As of the 1987 revised edition of Pedestrian Planning and Design, John Fruin (a leading researcher in the pedestrian dynamics) estimated that over 12 million people within the American population had physical issues which limit their mobility. He also cites that the increase in life expectancy has increased the number of people with limited mobility whether from disease or age. By the mid 2000’s the number of people in America who reported having some form of disability was nearly 54 million (18.7%) of the population and within general disabilities the rate of physical disability was 12.3 % (Brault 2008),. This which would give an estimate of about 6.5 million people with physical disabilities out of a population of 289 million. That rate corresponds to 2 in every 100 people having a physical disability.

Walking requires nearly continual shifting of the center of gravity within the body which requires muscular control (Ko 2010, 2012). The larger the individual the more strain it puts on the muscles and bones within the body, which could indicate that obese individuals will be able to perform at the same physical capabilities during a longer duration, though they may not be considered disabled. This remains relatively unstudied at a macro level, though there are studies which have been done within kinesiology on the micro movements of larger individuals (Ko 2010, 2012).

To further improve the understanding of the role that an increase in body size would play in evacuation times it could be recommended that further information be found between obesity related (or caused) disease and mobility impairment rates and types. A better understanding of mobility impairments as they relate to obesity could help refine results and accuracy of data input into models.

Chapter 9: Conclusions

All of the information investigated in the literature review for this thesis highlighted that there is a great need for more data to be collected and investigated in regards to human movement. Computer models are well verified against regulatory standards but there is still a low number of validation cases for which a model can be tested against for accuracy. Most of the investigation into the basics of human movement occurred nearly 50 years ago in the investigation of planning for pedestrian movement. Since then the demographics, specifically in America have changed and data has not been well documented regarding these changes. The validation cases which are present are still vastly collected in cities or under controlled circumstances and may not be representative of true emergency scenarios or of the particular characteristics of the society as a whole.

The complexity of building design and the increase of high rise buildings as well as non-traditional building design also impacts the evacuation process. Performance based design is a more common practice today than ever before and evacuation modelling is often an important characteristic and requirement of that process. In order to protect life safety interests performance based designs are reliant on a wholistic overview and the importance of a proper evacuation analysis should not be overlooked. If pedestrian dynamics are impacted by the increase in body size which American society has seen over the last couple of decades it is important that they be incorporated into modelling designs and literature so that the user and researcher knows what the proper inputs and options are with regard to body size and mobility issues.

In addition to the need to investigate data further for accuracy there is also a potential to investigate changes to the hydraulic formulas used in hand calculations. Though the hand calculations described in the SFPE Handbook of Fire Protection Engineering show relatively conservative outcomes for the total evacuation times it is clear from the discussions above that the density incorporated into the formulas is representative in terms of persons/m^2. There is no incorporation of actual body size into these formulas, and as it is shown in the MassMotion and Pathfinder scenarios there is likely a difference in the evacuation time with larger average body sizes. Further examining density as a function of the non-dimensional form as discussed in Chapter 5 could be helpful in modifying the expectations for estimates of egress time.

The hope is that this research will create an impetus for further research of the effect of mobility and size in the pedestrian evacuation dynamics field and improve the analysis of evacuation times with a more current representation of the American public. Understanding of the true characteristics of human movement and behavior is essential in preventing loss of life during emergency evacuation scenario.

Appendix A: Tabular Results

Table 9: Results of Test A

	Test	MassMotion	Pathfinder
Set 1	1	71	85
	2	77	101
	3	78	109
	4	82	122
	5	84	137
	6	88	144
Set 2	1	77	91
	2	76	97
	3	80	103
	4	87	117
	5	82	120
	6	91	127
Set 3	1	75	90
	2	78	98
	3	81	102
	4	84	127
	5	85	123
	6	84	135
Set 4	1	76	95
	2	79	93
	3	68	103
	4	87	112
	5	87	137
	6	88	143
Set 5	1	68	90
	2	76	100
	3	78	96
	4	80	114
	5	83	124
	6	85	140

Table 10: Results of Test B & C

	Test	Mass Motion		Test	Pathfinder	
Set 1	1	228	361	1	229	448
	2	253	370	2	249	506
	3	306	380	3	275	546
	4	303	380	4	311	641
	5	344	386	5	362	695
	6	349	401	6	387	772
Set 2	1	255	353	1	229	466
	2	261	371	2	245	480
	3	294	378	3	275	529
	4	280	393	4	303	600
	5	322	387	5	337	663
	6	330	399	6	378	756
Set 3	1	258	370	1	234	450
	2	271	364	2	241	492
	3	303	380	3	265	541
	4	272	386	4	310	590
	5	294	384	5	331	641
	6	317	392	6	373	715
Set 4	1	227	366	1	231	459
	2	255	373	2	258	494
	3	261	380	3	280	530
	4	300	386	4	293	570
	5	284	394	5	340	644
	6	329	381	6	368	710
Set 5	1	235	355	1	232	463
	2	244	364	2	246	491
	3	244	371	3	282	535
	4	282	389	4	294	586
	5	313	381	5	325	625
	6	305	394	6	353	685

The column immediately following the test column indicates the Test B results. The column to the right of that includes the results of Test C.

Table 11: Results of Test D

	Test	MassMotion	Pathfinder
Set 1	1	116	109
	2	119	114
	3	123	123
	4	127	129
	5	131	133
	6	137	143
Set 2	1	116	111
	2	119	117
	3	123	125
	4	127	129
	5	131	137
	6	139	142
Set 3	1	117	109
	2	120	116
	3	124	121
	4	129	127
	5	133	136
	6	140	140
Set 4	1	117	110
	2	121	114
	3	125	120
	4	128	125
	5	134	131
	6	141	139
Set 5	1	113	109
	2	117	111
	3	119	121
	4	123	126
	5	127	130
	6	133	136

Table 12: Results of Test E

	Test	MassMotion	Pathfinder
Set 1	1	63	95
	2	65	103
	3	67	109
	4	68	117
	5	72	119
	6	78	127
Set 2	1	62	94
	2	65	99
	3	68	106
	4	69	115
	5	74	121
	6	75	126
Set 3	1	63	92
	2	66	99
	3	69	104
	4	72	110
	5	72	117
	6	75	121
Set 4	1	62	94
	2	64	99
	3	66	104
	4	69	110
	5	71	115
	6	73	122
Set 5	1	61	91
	2	65	98
	3	67	105
	4	70	107
	5	73	113
	6	74	119

Table 13: Results of Test F

	Test	MassMotion	Pathfinder
Set 1	1	79	98
	2	83	105
	3	88	110
	4	93	119
	5	99	132
	6	93	145
Set 2	7	75	100
	8	87	110
	9	85	112
	10	89	116
	11	94	133
	12	102	144
Set 3	13	81	102
	14	86	109
	15	89	110
	16	89	118
	17	90	124
	18	104	148
Set 4	19	83	108
	20	87	104
	21	93	117
	22	96	120
	23	98	123
	24	95	143
Set 5	25	75	109
	26	83	109
	27	89	113
	28	90	118
	29	95	125
	30	98	145

Appendix B: Hand Calculations

Test A:

1.Total persons: 100 (Assume 1st person is at the exit when the evacuation begins)

2. Controlling Element: Single Exit Door 1 meter wide.

   Boundary layer: 15cm on each side (.15m x 2)= .30m

3. Effective width (We): 1.0m -0.3m =0.7m

4. Max Specific Flow (Fsm)=1.3 for doorways

5. Fc (Flow Rate)= Fsm *We = 1.3 (p/ s*m of We) *0.7m

   =0.91 (p/s)

6. Time for total population to pass through element: 100 persons/0.91 p/s = 110 Seconds

7. Last person from queue to exit (outside): S= 0.469 m/s

   Dist= 8.38 m

   Time 17.8 Seconds.

   Total time = 110 Seconds +18 Seconds

   Total time =128 Seconds

Tests B & C:

1. Total persons 1000 (assume the 1st person is at the exit when the evacuation begins)

2. Effective Width (We)=1.0m -(15cm*2)= 0.70m for each door

3. Speed: S=k-akD

   =1.40-(0.266*1.04*1.667)   =0.779 m/s

4. Fs=S*D

   =0.779 m/s *1.667 Persons/m^2

   =1.29 persons/m-s

5. Fc=Fs*We

   =1.29 persons/m-s *0.70

   =0.903 persons/s (per door)

6. Total Fc=0.903 persons/s*4 doors

   =3.612 persons/s

7. Total Time: Tp=P/Fc

   =1000/3.621

   =276.1seconds

   =4 m 27 seconds

1.1 With 2 doors the total Fc

   =0.903 persons/s *2 doors

   =1.806 persons/s

1.2 Tp=1000 persons/1.806 persons/s

   =553.7 seconds

=9 minutes 14 seconds

Test D

This test requires an individual to make some assumptions about the stairs and ceiling height as the specific geometry is not noted. For this test it is likely that the stairs would be 7/11 risers and treads. It is also likely that the ceiling would be at 3.0 meters. These dimensions are considered standard and have been assumed for the hand calculation that follows.

1. Determine effective widths (We)= Total Width - Boundary Layer

    i. Corridor= 2.0m-(2*(0.2))= 1.6m

    ii. Stair= 2.0-(2*(0.15))=1.7m

2. Determine Controlling element:

    a. $Fc_{Cooridor}$=1.3 * 1.6= 2.08 persons/s

    b. Fc_{Stairs}=1.01*1.7=1.71 persons/s

    c. In this case the controlling element is the stairs because it has the lower controlling flow value.

3. Determine flow time for Controlling element:

    a. 150 persons/ 1.71 persons/s = 88 seconds

4. Determine time or the first person to Controlling Element:

    a. Total Distance to stairs =12 m

    b. V=k-akD

        i. Assume D=1.88 per/m^2

        ii. For Cooridors k=1.4, a=0.266

iii. v=0.6998 m/s

iv. 12m/0.6998m/s =17 seconds

5. Determine time of travel of last person from queue to exit:

   a. Total distance of stair travel =5.61m

   b. S=k-akd

      i. Assume D=1.88per/m^2

      ii. For Stairs k=1.08 a=0.266

      iii. S=0.53 m/s

      iv. 5.61m/ 0.53 m/s =11 Seconds

6. Sum the times to get total time to egress:

   a. 116 Seconds

   b. 1 Minute 56 Seconds.

Test E:

This is the most simple of experiments for hand calculations:

1. The controlling element is automatically the corridor

2. The Fc value is 1.3* We (0.72m)=0.936 persons/sec

3. 100 persons/ 0.936 persons/s = 107 Seconds for flow through corridor.

Test F:

1. The controlling element will be the exit corridor
    a. 1.2m-0.4m = $Fc_{corridor}$ 1.04
2. Time for First person to reach the controlling element
    a. 3 meters total distance
    b. S= 0.69 m/s
    c. 3m/0.69 m/s
    d. 4.3 Seconds
3. Last Person to Exit
    a. 8 meters total distance
    b. 8m /0.69m/s
    c. 11.5 Seconds
4. Total time for occupants to pass through controlling element
    a. 100 people/ 1.04
    b. 96 Seconds
5. Total: 96 seconds+11.5 seconds+4.34 seconds = 112 Seconds

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