ABSTRACT

Title of thesis: DEVELOPING A VELOCITY-DENSITY CURVE FOR HIGH-DENSITY CROWD SIMULATION BY ANALYZING FOOTAGE VIDEOS

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Crowds with densities higher than 2 persons/m^2 can be defined as high-density crowds. High-density crowds presenting in daily life like concerts and sports events can lead to serious people and property loss. This research work focuses on developing a new speed-density relationship for high-density crowds. The applicability of the new speed-density relationship is tested in Pathfinder, an agent-based evacuation simulation software developed by Thunderhead Engineering, to determine the impact of updating such data on the model's performance. This research also discusses several parameters and functions in Pathfinder including acceleration time and reduction factor to help model high-density crowds.

Previous work is available for analyzing crowds with densities lower than 3 persons/m^2. However, densities as high as 9 persons/m^2 are common in many high-density crowd scenarios. The disparity between previous work and real-world situations

presents a challenge for engineers to understand the crowd dynamics of high-density crowds. Developing evacuation models to predict the behavior of high-density crowds is crucial to improving the predictive ability of crowd simulation. By doing so, it helps to reduce the number of casualties in future emergencies.

Real-world footage videos are analyzed in this research. With the open-source experimental footage videos provided by Jülich, a national research institution, a new speed-density curve is summarized by collecting and analyzing data from the videos. The assessment of the applicability of the new speed-density in Pathfinder focuses on four aspects: evacuation time, flow density, flow velocity, and occupants' arrangement.

Per case examined, by applying the new speed-density curve, the predicted evacuation time from Pathfinder simulation is improved from 12.6% to within 4.9% of the experimental video time. The predicted flow density is improved from 6.2% to within 0.7% of the average video density. The predicted flow velocity is improved from 25.9% to within 3.3% of the average video velocity. At the same time, it is observed that occupants in the model behave more realistically.

DEVELOPING A VELOCITY-DENSITY CURVE FOR HIGH-DENSITY CROWD SIMULATION BY ANALYZING FOOTAGE VIDEOS

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Masters of Science
2023

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ACKNOWLEDGEMENTS

I would like to express my great thanks to Dr. Milke. When I just started my M.S. program, Dr. Milke provided many research ideas and we decided to explore this topic in the end. Dr. Milke also invited me to work as a teaching assistant for online courses which helped me get some funding for my research. During this research, Dr. Milke always helped me to find right directions and suggested different ways of tackling problems. When I was writing this thesis, Dr. Milke advised me on organizing the content and paying attention to many aspects that were easily overlooked.

I also would like to thank Dr. Steve Gwynne and Dr. Bryan Klein for sharing many professional opinions and guiding me to know more about the use of Pathfinder. During this research, Dr. Gwynne provided many feedback and suggestions when I got new progress. Dr. Klein helped to explain and solve Pathfinder problems every time the results did not meet our expectations.

In terms of wording for this thesis, I would like to thank Dr. Milke, and my friend, Siddharth Sharma. At the same time, I would like to thank my friend, Yiren Qin, for helping me with MATLAB programming. I would also like to thank my friend, Yujeong Kim, Yifang Gui, Yihan Fang, Zihan Chen, and Zhen Liu for helping me with all challenges and difficulties I faced these years studying in the U.S.

In the end, I would like to thank my parents and families. They always supported and encouraged me whenever I felt stressful and upset in my life. Thanks for staying with me spiritually all the time.

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CHAPTER 1: INTRODUCTION

1.1 NATURE OF THE PROBLEM AND MOTIVATION

Crowds with high densities can be present in numerous situations such as concerts, sports events, festivals and religious activities. However, during an emergency in the presence of a high-density crowd, the resulting threat to people and property can be particularly severe. According to statistics, in 2021, at least 100 people were killed and 487 people injured as a result of crowd disasters. [1]

1.1.1 SEOUL HALLOWEEN CROWD CRUSH

On the night of October 29th, 2022. During the Halloween celebrations in the Itaewon neighborhood of Seoul, South Korea, a high-density crowd created a crush incident, which claimed the lives of 159 individuals and injured 196 others.

Videos made by eyewitnesses depicted a massive crowd of people, squeezed into a narrow alley, with bodies tightly packed and compressed to a depth of five or six individuals. One attendee said that a group of young men began pushing others, which caused people to stumble and fall, and then the crush quickly escalated. Survivors of the crush reported that they were unable to escape because the narrow alleyway was surrounded by establishments that had closed for the night and blocked their entrances.

After the tragedy, the police acknowledged that they had insufficient officers to control the large crowd. They also admitted to not having a crowd control plan in place for the Halloween festivities because there was no central organizer. The government claimed that the overwhelming crowd was unpredictable, but experts disagreed and argued that authorities should have anticipated the large crowd due to the relaxed COVID-19 rules. [2]

1.1.2 THE STATION NIGHTCLUB FIRE

On the evening of February 20, 2003, a tragic incident took place at The Station, a hard rock music venue and nightclub located in West Warwick, Rhode Island, United States. During a concert by the rock band Great White, a pyrotechnic display ignited flammable acoustic foam in the walls and ceilings surrounding the stage, causing a fire that quickly spread throughout the entire building. The fire resulted in the loss of 100 lives and injured 230 people.

Initially, there was no panic as people just turned their attention towards the commotion. Despite the flames not being too severe in the other rooms and the smoke not having reached them, most individuals remained rooted to the spot. However, as more people noticed the fire and began to turn towards the exit, a bottleneck formed, causing people to push and shove their way out of the front door.

Upon realizing that no one was exiting through the back door anymore, one attendee went around the back and attempted to help people escape through a side window, managing to assist one person in crawling out. Returning to the front entrance, the attendee saw people piling on top of each other, struggling to escape from the front door. The black smoke was pouring out over their heads at that time, making it even more difficult for them to exit. [3]

1.1.3 KISS NIGHTCLUB FIRE

On January 27, 2013, a deadly fire broke out at the Kiss nightclub in Santa Maria, Rio Grande do Sul, Brazil, claiming the lives of 245 individuals and causing injuries to a minimum of 630 others.

According to Brazilian police, the Gurizada Fandangueira band triggered the devastating fire at the Kiss nightclub by igniting a pyrotechnic device while performing on stage. The flare ignited the acoustic foam on the ceiling. The authorities also cited other factors that contributed to the high death toll, such as the absence of emergency exits (the only entrance and exit was the front door) and the overcrowding of the nightclub, which exceeded its maximum capacity by hundreds of people.

Numerous fatalities occurred as individuals attempted to seek refuge in the restrooms or mistakenly thought they were exits. Officials removed approximately 180 bodies from the bathrooms. In addition, over 150 individuals were injured due to the stampede at the front door and the fast accumulation of smoke inside the nightclub. [4]

1.1.4 GloRilla CONCERT IN NEW YORK

Following the performance of GloRilla and Finesse2tymes on the night of March 6^{th}, 2023, at Rochester's Main Street Armory, people surged dangerously toward the exits shortly after 11 p.m., for unfounded fears of gunfire. Two women were killed because of the stampede. [5], [6]

Experts in crowd safety explained that a crowd can rapidly become unstable when the density exceeds eight to nine people per square meter, and individuals trapped in the crowd will begin to lose consciousness within 30 seconds. Once a crush is underway, there is little that can be done to save the victims. Thus, the key to preventing such disasters is adequate training in crowd control and the monitoring and dispersing of crowds well before they reach the critical density. [2]

Although the simulation of crowd dynamics and behavior has become prevalent with crowd simulation, most of the current studies are limited to simulating particular scenarios. While recent advances have attempted to incorporate various individual behaviors for a more realistic simulation outcome, the process remains highly complicated and often needs significant modifications. [7]

Here are the key tasks performed in this research work:

- Pre-test model simulations in Pathfinder.
- Develop the new speed-density curve by video analysis.
- Test the new speed-density curve by modeling.

CHAPTER 2: LITERATURE REVIEW

2.1 CURRENT STUDIES

Lately, many studies have been done to develop new crowd models and to study crowd dynamics. Researchers usually focus on discussing several criteria: flow, density, velocity, and position of each individual. Shanwen Yang et al. [8] identified that velocity-based models offer high scalability and can simulate a wide range of micro phenomena, such as leadership, group dynamics, pressure, and lane formation. These models focus on individual characteristics, such as step size, gender, personal space, and visual range, and are generally more consistent with real-world pedestrian behavior. Kuligowski [9] mentioned that in some models, users have to provide the model with speed, flow, and density values for each space in the building. This shows that speed, flow and density are key parameters in the evacuation models. Zhenzhen Yao et al. [10] discussed the relationship between crowd density and velocity to prove the validity of their proposed method in crowd simulation. Bellomo et al. [11] analyzed different mathematical structures correspond to different modeling scales: microscale, macroscale, and mesoscale. Those mathematical structures took velocity, density, acceleration, and walker's position into consideration.

Videos are recorded by camera or provided from open sources. Tracking software packages are tested to analyze pedestrian trajectories. [12] Velocity, location, and flow are recorded based on time. Those data from real-world videos can help study crowd dynamics including relationships between flow, density, and speed. Johannsson et al. [12] discussed crowd dynamics and crowd safety based on video analysis and addressed the speed-density and flow-density diagrams.

Literatures above show that many studies paying attention to analyze density-velocity relationship to discuss crowd dynamics or to show the improvement of a new model. Research work was done to show speed density data obtained for individuals traversing specific egress paths. Figure 2-1 is a scatterplot which shows a comparison between speed-density curves with data obtained for individuals.

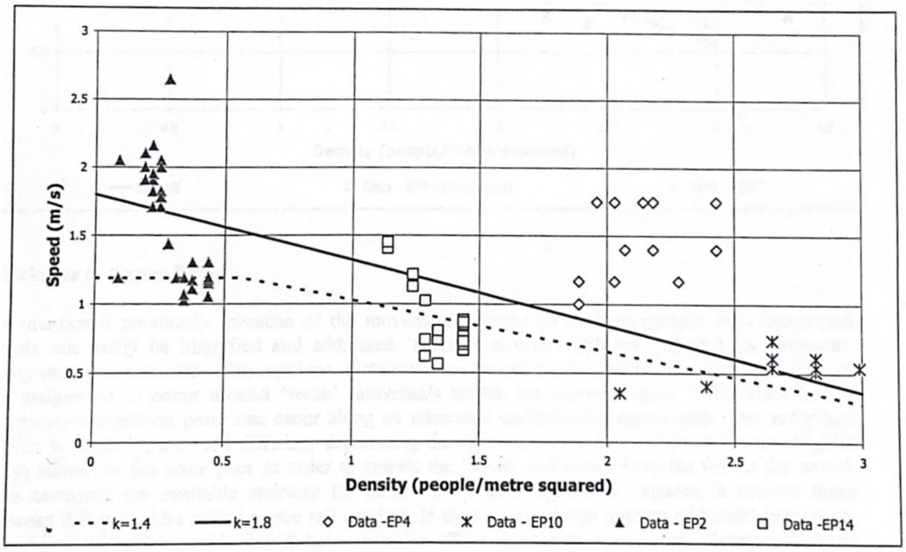

Figure 2-1: Movement speed as a function of density for several walkway egress paths at stadia. [13]

According to Gwynne and Rosenbaum [14], there is a linear function between speed and density. The equation of this function is:

$$S = k - akD \qquad 2\text{-}1$$

where

S = speed along the line of travel

D = density in persons per unit area

k = constant, as shown in Figure 2-2

= k_1; and a = 2.86 for speed in ft/min and density in persons/ft^2

= k_2; and a = 0.266 for speed in m/s and density in persons/m^2

Exit route element		k_1	k_2
Corridor, aisle, ramp, doorway		275	1.40
Stairs			
Riser (in.)	Tread (in.)		
7.5	10	196	1.00
7.0	11	212	1.08
6.5	12	229	1.16
6.5	13	242	1.23

1 in. = 25.4 mm

Figure 2-2: Constants for Equation 2-1, evacuation speed. [14]

The curve used by Gwynne and Rosenbaum is a simplification and it captures a conservative estimate of potential movement. The curve indicates that when the density reaches 1.88 persons/m^2, the specific flow is maximized. Specific flow is the flow of evacuating persons past a point in the exit route per unit of time per unit of effective width. The effective width is the usable width of the component, i.e. the clear width minus a small width at the edges which is not used. A density greater than 2 persons/m^2 can be defined as high density and routine movement declines and eventually becomes uncomfortable above that density. The correlation by Gwynne and Rosenbaum also indicates that no movement will take place if the population density exceeds about 3.8 persons/m^2. [14] However, in many high-density crowd scenarios, the crowd density could be as high as 9 persons/m^2. [15], [16] This gap between current research results and real-world situation makes it difficult for engineers to understand the crowd dynamics of high-density crowds.

To enable modeling to predict the actions of high-density crowds and to reduce losses in the event of an emergency, this research is going to focus on developing a new velocity-density curve to help better understand a dense crowd flow. This research can fill the gap by studying the velocity-density relationship at high density levels over 2 persons/m^2 by video analysis. Such a process will improve the predictive ability of crowd simulation and therefore help to reduce the number of casualties in future emergencies.

2.2 MODEL DESCRIPTION

Computational modeling is a method to study human movement and predict evacuation time. This section focuses on describing one evacuation model, Pathfinder, which has been used for this research. The description includes calculation rules and several key functions in Pathfinder.

2.2.1 PATHFINDER

Pathfinder is an agent-based evacuation simulation software developed by Thunderhead Engineering. It is a human movement simulator originally designed to represent unidirectional crowd movement in moderate densities during an evacuation from fire. Occupant movement modes in Pathfinder include primarily the Society of Fire Protection Engineers (SFPE) and Steering modes. In the SFPE mode, evacuation routes are selected using the length of the walking path as the primary reference standard. Occupants will select exits based on the principle of proximity. During the simulation, it automatically recognizes the density of the evacuation space to adjust the speed of the occupants. In this mode, the exits restrict the flow of occupants. The Steering mode allows occupants to complete their current movement objectives and be able to react to changing circumstances. The evacuation strategy is developed by combining a route plan and occupant collisions. The path is determined by the evacuation distance and the distance between occupants. In addition, exits do not restrict the flow of occupants. [17]

In the steering mode of Pathfinder, density is calculated based on the spacing between nearby occupants, as well as the relationship between the average longitudinal and lateral spacing densities, which is shown in Figure 2-3. [18]

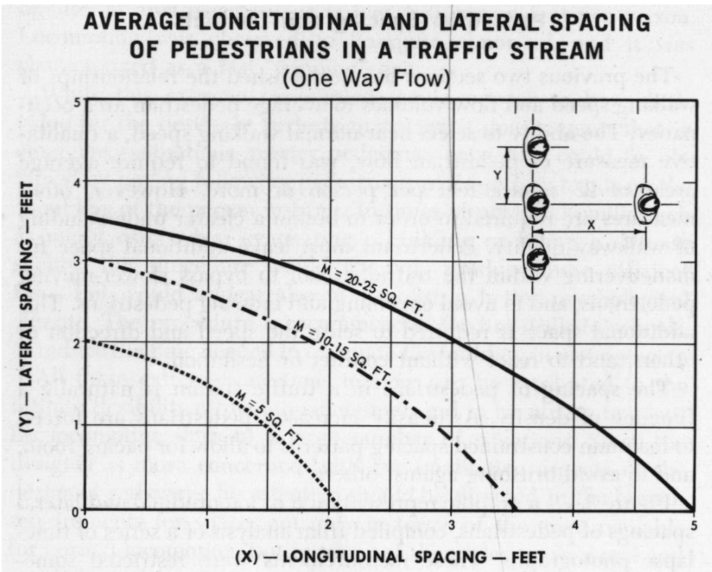

Figure 2-3: Average Longitudinal and Lateral Spacing of Pedestrians in a Traffic System. [18]

In Pathfinder, the density lines in the figure are treated as contours that are estimated as ellipses. These contours are mirrored around the Y=0 axis. To determine an occupant's density, the X axis in the figure is aligned with the occupant's current velocity, and the origin is set to the occupant's location, creating a local coordinate system. The location of each nearby occupant is then transformed into this local coordinate system. Occupants with a local coordinate X value less than 0 are ignored to prevent occupants behind from affecting an occupant's speed. For occupants with local $x \geq 0$, the density for the occupant is determined by the density associated with the closest person to the occupant which yields the maximum density. [18]

As occupants move along their path, a modified maximum velocity ($\acute{v}_{max}$) is determined based on their current terrain, the specified maximum velocity (v_{max}), and the spacing of surrounding occupants. The surrounding occupant spacing is utilized to estimate the occupant density (D), which is then incorporated to calculate $\acute{v}_{max}$. [18]

2.2.2 KEY PARAMETERS USED IN PATHFINDER

Here are several settings and functions in Pathfinder that may help understand the flow behavior. The explanations of key settings and functions used in this research are as follow [17]:

- Measurement region: produces time history data for velocity and density within a designated area of the navigation mesh.
- Debug mode: when the Debug mode is activated, a runtime visualization is displayed to demonstrate the progress of the ongoing simulation.
- Reduction factor: this factor, which is unitless and should be chosen between 0 and 1, assists occupants in navigating through crowded spaces by allowing them to pass each other more easily. The default for the reduction factor is 0.7.
- Personal distance: the preferred distance that an occupant in a queue will attempt to keep from those around them. The default value is 0.08 m.
- Acceleration time: a parameter of the Steering Mode that defines the duration required

for an occupant to attain maximum velocity from a standstill or come to a stop from maximum velocity. The maximum velocity in this research is 1.19 m/s and the default value of the acceleration time is 1.1s.

- Minimum diameter: when there are geometries that make it challenging for occupants to move around, this feature can be activated to modify the collision test between the occupant and geometry, so that it can accommodate the narrower space. The default value is 33 cm.

CHAPTER 3: SIMULATING CROWDS IN PATHFINDER

Because later in this research, video analysis is applied to obtain speed density data in Chapter 4. This chapter discusses the type of scenarios selected for the video analysis by modeling. Several key parameters mentioned in section 2.2.2 are also tested to help better simulate crowds with high densities. Methods of obtaining velocity and calculating density are also introduced.

3.1 DENSITY CALCULATION METHODS

This section introduces four density calculation methods. section 3.1.1 introduces the method in Pathfinder and section 3.1.2 introduces the other three methods developed in this research.

3.1.1 DENSITY CALCULATION IN PATHFINDER

When a measurement region is applied to measure speed and density in a certain area, it provides the weighted average results happening inside the region. In measurement regions, density and velocity are calculated using Steffen and Seyfried's Voronoi diagram-based method [19]. The method involves the creation of a Voronoi diagram to divide the space among occupants into cells (Figure 3-1). Each occupant's density is calculated based on their cell's size in the diagram. These densities are then combined using a weighted average, where the weights are determined by the portion of the measurement area that intersects with the Voronoi cell. Even when two occupants have similar densities, the location of the occupant in the measurement region may lead to different density and velocity results. [18]

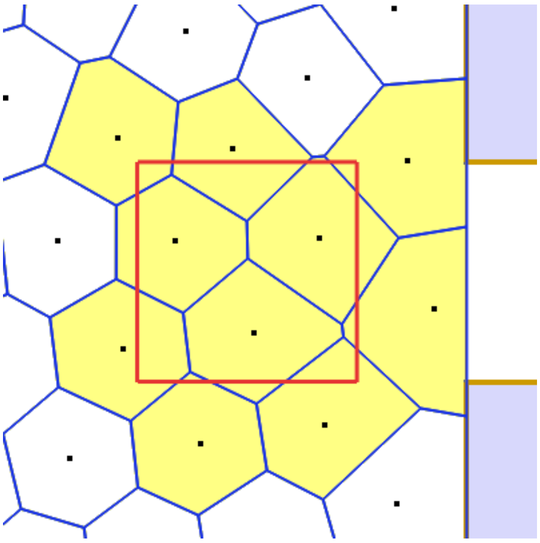

Figure 3-1: Intersection of a measurement region and nearby occupants' Voronoi cells.

[18]

3.1.2 DENSITY CALCULATION WITH IMAGE PROCESSING

Method in section 3.1.1 works for calculating group densities. The following method focuses on tracking individual's density and is developed and applied during this research work.

When calculating a single person's density is required, the Debug mode of the Pathfinder can help users to apply detailed analysis for each occupant in the model. The user needs to take screenshots while running the simulation in Debug mode and use a MATLAB program to conduct image processing. Figure 3-2 is a sample screenshot in Debug mode. The yellow dot in the screenshot is the tracked individual. Density of this tracked individual will be calculated later.

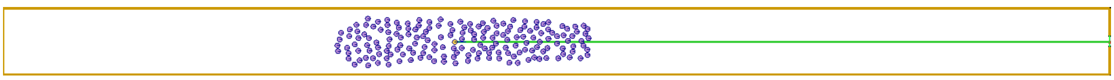

Figure 3-2: Sample screenshot in debug mode.

When Figure 3-2 is imported into the MATLAB program for analysis, the program allows users to set the maximum X and Y coordinates. Here, the maximum X and Y values are the length and width of the model in centimeter. Figure 3-3 shows the MATLAB interface after setting the maximum X and Y values.

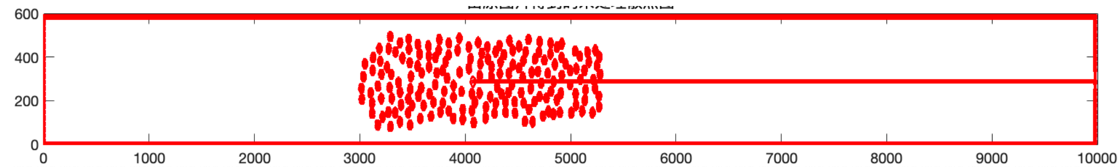

Figure 3-3: Processed sample screenshot in MATLAB.

Next, four points are selected around the tracked individual to locate the individual in a square. The MATLAB program can provide the coordinates of each selected point. The four points selected in the Figure 3-3 are shown as the four black dots in Figure 3-4.

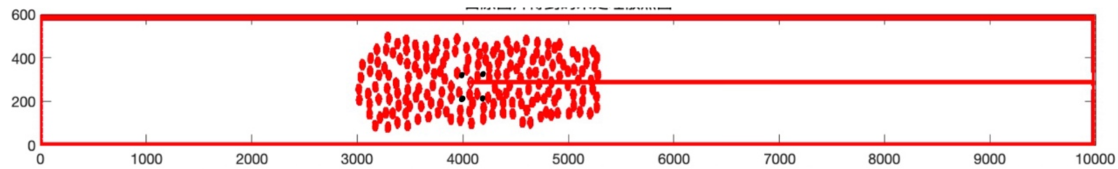

Figure 3-4: Four points selected in the sample screenshot.

The corresponding coordinates of the selected four points generated by the MATLAB program are:

(4009.0, 333.5196) (4188.5, 333.5196)

(4009.0, 212.8492) (4188.5, 212.8492)

Based on these four coordinates, $\Delta x = 179.5\ cm\ and\ \Delta y = 120.7\ cm$. Thus, the area of the square is $\Delta x \times \Delta y = 179.5\ cm \times 120.7\ cm = 2.17\ m^2$. There are four people included in the square, so the density of the selected individual can be calculated as:

$$D = \frac{4\ persons}{2.17m^2} = 1.84\ persons/m^2 \qquad 3\text{-}1$$

However, when the above process is applied, one question is raised: when the four points are selected to form a square, should the individual be located at the middle of the square or at the edge of the square? That is, which part of the crowd should be considered when calculating density. Here, three sub-methods: Method_1, Method_2, and Method_3 are created. Explanations of these three sub-methods are listed below:

- Method_1: the density of crowd behind a pedestrian is calculated.
- Method_2: the density of crowd around a pedestrian is calculated.
- Method_3: the density of crowd in front of a pedestrian is calculated.

If the yellow dot indicates the tracked pedestrian, Method_1 is shown as Figure 3-5, Method_2 is shown as Figure 3-6, and Method_3 is shown as Figure 3-7.

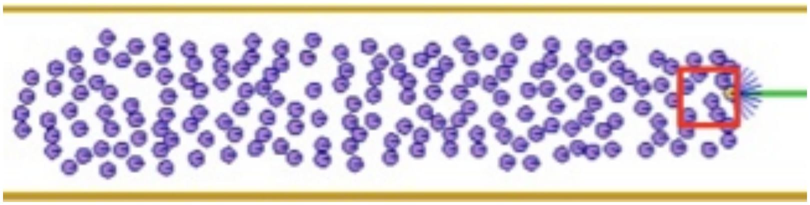

Figure 3-5: Example of Method_1.

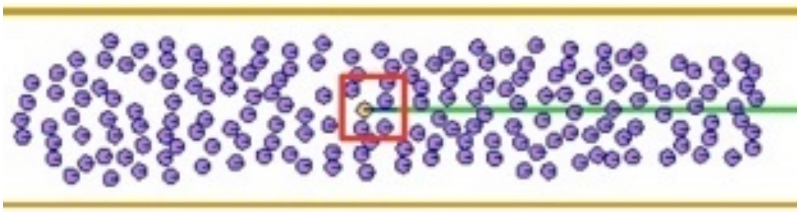

Figure 3-6: Example of Method_2

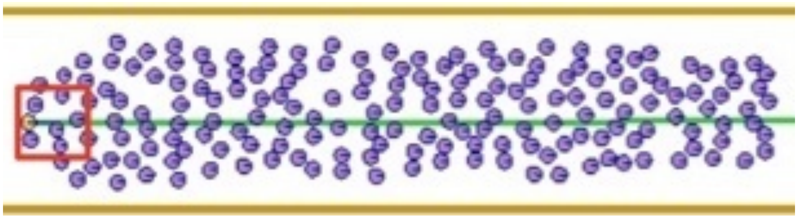

Figure 3-7: Example of Method_3

Applicability of these methods will be discussed later in section 3.4.

3.2 MODELING FLOW IN SPACES WITH DIFFERENT SHAPES

Section 3.1 includes two density calculation methods related to this research work. These two methods will be applied to conduct analysis and to explain results in later chapters.

In this section, two common scenarios that may generate high density crowds, a square room and a hallway, are modeled to decide the video of which scenario should be analyzed to study crowd flow in Chapter 4. Comparisons are made between two models and results are applied to an advanced model for further analysis.

3.2.1 LARGE SQUARE AREA MODEL

In the large square area test, a room with dimensions of 21 m by 21 m is created and 100 occupants are randomly distributed in a 4 m by 5 m area at the center of the room. A 3 m wide exit is located on each side wall. Three sizes of measurement regions are applied in the room: 5 m by 5 m, 4 m by 4 m, and 3 m by 3 m. Since Pathfinder allows measurement regions to overlap each other, the locations of measurement regions are indicated in Figure 3-8.

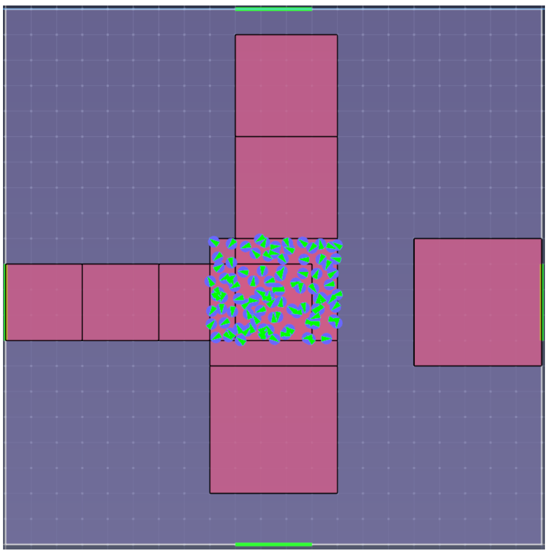

Figure 3-8: Location of measurement regions in the big square area test.

In this model, occupants can freely choose the exits. At the start of the simulation, the density of crowds is 5 persons/m^2. As occupants spreading out to exits, densities decrease until 0 and no line is formed near exits.

The acceleration time function is activated in this test. Three different acceleration times are tested separately: 0.1 s, 0.5 s and 1.1 s. Results are summarized for different acceleration times.

3.2.2 HALLWAY MODEL

In this hallway test, a 6m by 100 m long hallway is modeled with a 2 m wide door at the right end. 180 occupants are distributed in a 6 m by 6 m area at the left end of the hallway. Occupants move from the left end to the right end to exit. Three sizes of measurement regions are tested: 6 m by 6 m, 4 m by 4 m, and 2 m by 2 m. The measurement regions are located as Figure 3-9.

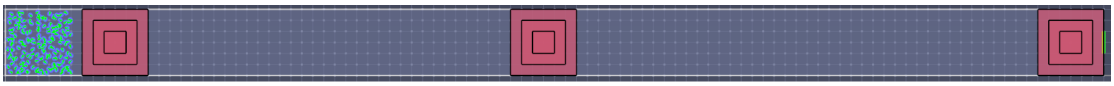

Figure 3-9: Location of measurement regions in the hallway test.

In this model, occupants move along the hallway from the left end to the right end. Densities start as 5 persons/m^2 and decrease when the occupants move along the hallway. Densities increase to 2.97 persons/m^2 when occupants reach the exit and form a queue.

The same three acceleration times are tested separately as the square area test. Discussions are made based on different acceleration times.

3.2.3 COMPARISON BETWEEN THE OUTCOMES OF THE SQUARE AREA TEST AND THE HALLWAY TEST

Mentioned in section 2.1, a density greater than 2 persons/m^2 can be defined as a high density. Because this research emphasizes speed density relationship in high density situations, discussion will focus on data with densities higher than 2 persons/m^2.

To compare the results from simulations in sections 3.2.1 and 3.2.2, data is summarized and classified based on different acceleration times. For each model, data from all the measurement regions with the same acceleration time are summarized. Data points with different acceleration times are plotted on the same graph. Graphs for the large square area model and the hallway model are respectively presented as Figure 3-10 and Figure 3-11.

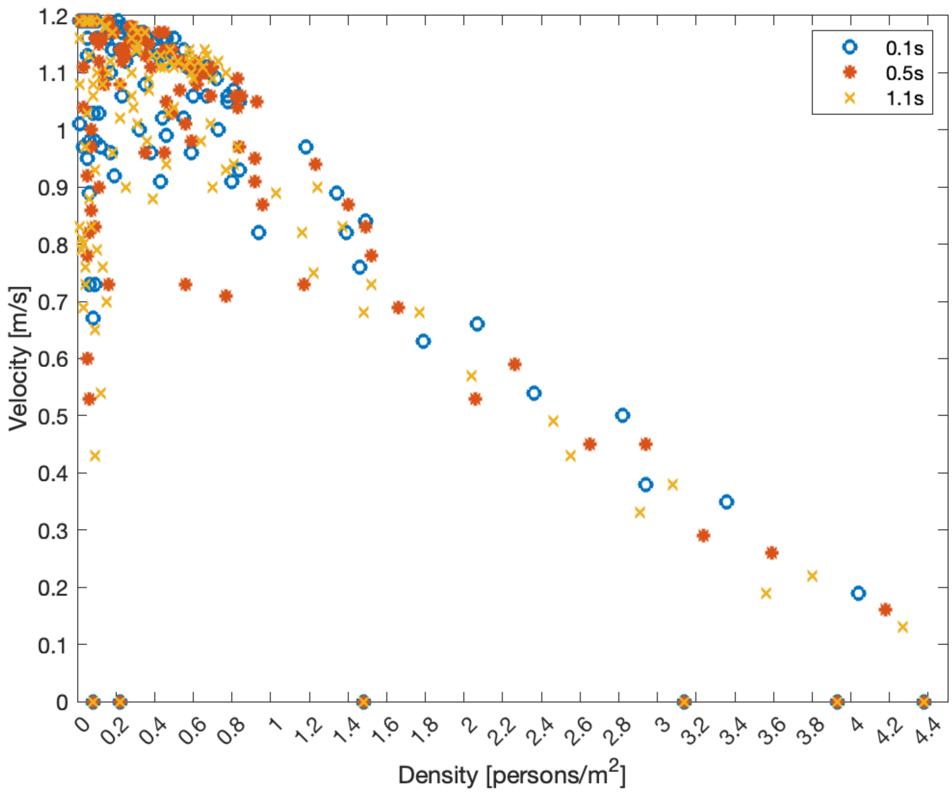

Figure 3-10: Results with different acceleration times in the large square area test.

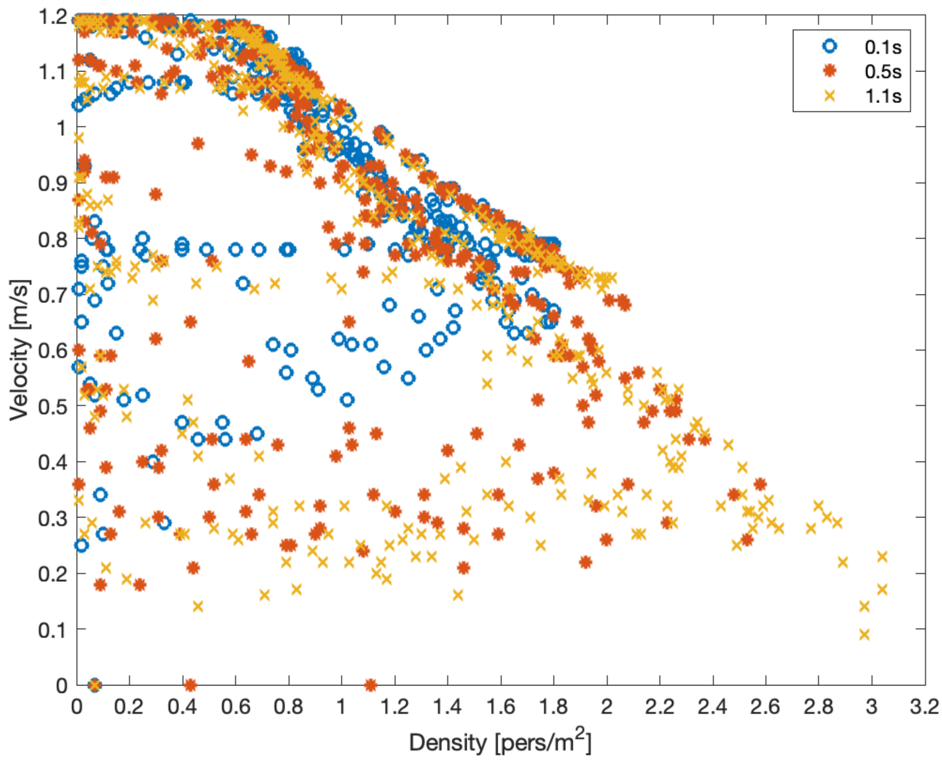

Figure 3-11: Results with different acceleration times in the hallway test.

Based on the two plots in Figure 3-10 and Figure 3-11, results from the large square area model are scattered mostly where the density is less than 1 persons/m^2. Variation increases at densities lower than 1 persons/m^2 since with low densities, density no longer constrains movement and agents can travel at their chosen speed.

However, results from the hallway model are scattered evenly until the density reaches 2.6 persons/m^2. Because data with densities greater than 2 persons/m^2 are the research targets, Figure 3-10 and Figure 3-11 show that the hallway model can provide more data with densities higher than 2 persons/m^2 which is a better choice for simulating high-density scenarios. For this reason, footage videos recorded in hallways are selected for future analysis in this research.

To discuss the application of parameters in Pathfinder, focusing on analyzing one model can be a way. Based on the discussion above, the hallway model is analyzed.

According to Figure 3-11, when the acceleration time is 0.1 s, no data is available above 1.8 persons/m^2. However, with an acceleration time of 1.1 s, data is available above 2.6 persons/m^2. Acceleration time is related to the acceleration of occupants. According to the introduction of acceleration time in section 2.2.2, the resulting forward acceleration of each occupant is **forward_acceleration = max_speed/accel_time**. Consequently, when the acceleration time is 0.1 s, the forward acceleration is high, and occupants will quickly speed up to reach the group in front as long as there is enough space. So, crowd spreads out quickly and maintains a relatively low density. Thus, the default value of the acceleration time in Pathfinder, 1.1 s, is better at creating scenarios with densities higher than 2 persons/m^2.

If a detailed look is taken for the hallway model with a 1.1 s acceleration time, discussion about different measurement regions can be made. Results exported for different sizes of measurement regions are summarized as Figure 3-12.

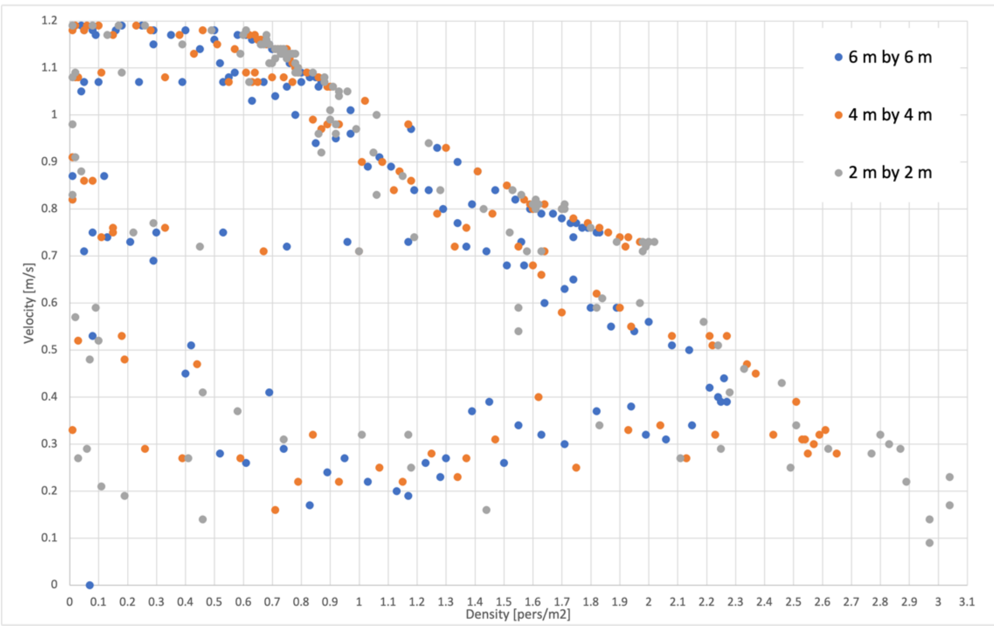

Figure 3-12: Results within different sizes of measurement regions from the hallway model with 1.1s acceleration time.

Based on the plot in Figure 3-12, the 4 m by 4 m and 2 m by 2 m measurement regions are able to provide results above 2.3 persons/m^2, while there is no data available for 6 m by 6 m measurement region. This indicates that the size of measurement region between 4 m by 4 m and 2 m by 2 m is better. A 3 m by 3 m measurement region should be applied for further analysis.

By revising the hallway model, it is noticed that the first measurement region should be located at the far-left end of the hallway instead of in front of the crowd. Because by doing this, the beginning movement of the crowd with a density of 5 persons/m^2 can be tracked. If the first measurement region is in front of the crowd, occupants will gradually enter the measurement region, and this cannot help to study crowd dynamic at the start of movement. The width of the exit can also be changed to 1 m to create queue near the exit.

Based on the analysis and discussion above, some changes are made to the hallway model to create an advanced model in section 3.3.

3.3 ADVANCED MODEL

This section focuses on the advanced model. This advanced model includes the new changes in the hallway model described in section 3.2.3.

3.3.1 ADVANCED HALLWAY MODEL

The advanced hallway model is built based on the hallway model. The width of the exit is changed to 1 m. The size of the measurement regions is changed to 3 m by 3 m, and the farthest left measurement region is moved right next to the left wall. All other parameters including reduction factor, acceleration time and personal distance are kept as their default values. Configuration of the advanced model is shown in Figure 3-13.

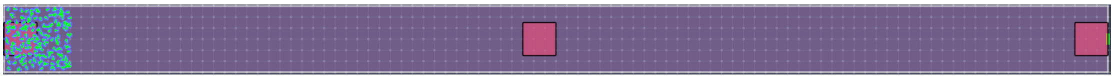

Figure 3-13: Advanced hallway model.

3.3.2 DISCUSSION ON THE ADVANCED HALLWAY MODEL

This section discusses the improvements and questions gained from the results of the advanced hallway model. Data collected from the measurement regions in the model are summarized in Figure 3-14.

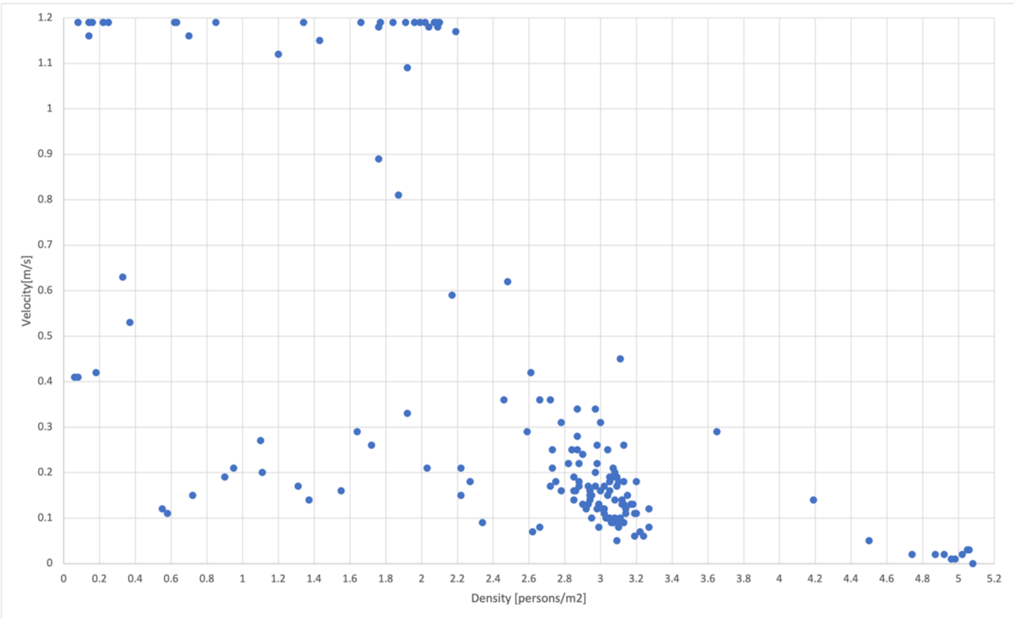

Figure 3-14: Results exported by the measurement regions from the advanced hallway model.

Results show that changing the location and size of the measurement regions can improve the high-density scenario simulation since densities above 4.6 persons/m^2 are indicated in Figure 3-14.

However, according to the SFPE speed-density equation for hallways [14]:

$$S = 1.40 - 0.266 \times 1.40D \qquad 3\text{-}2$$

If density is larger than 0.56 persons/m^2, the corresponding speed will be less than 1.19 m/s. In Figure 3-14, the maximum speed (1.19 m/s) occurs until density reaches around 2.2 persons/m^2, which is much larger than 0.56 persons/m^2. This can be caused by limited data and the density calculation method in Pathfinder. Mentioned in section 3.1.1, the location of the occupant in the measurement region may lead to different density and velocity results. If an occupant is speeding up to reach the group in front and it just entered the measurement region at that time, the density of the group in front will affect the occupant's density while the occupant is still moving with the maximum velocity.

Meanwhile, results for densities between 2.6 persons/m^2 and 3.4 persons/m^2 are varied. A one-to-one relationship for speed and density is not indicated in Figure 3-14. This is also caused by the density calculation method mentioned in section 3.1.1.

To better understand human behavior in the crowd, a single person tracking method is developed to help track individual's movement in the crowd.

3.4 SINGLE PERSON TRACKING METHOD

Single person tracking method focuses on collecting density and speed data of one individual at different times. This method helps better study one person's movement in a crowd. This method is also used in the later video analysis in this research.

To apply this method, run the advanced hallway model and enter Debug mode in Pathfinder while running the simulation. Debug mode can directly provide the velocity of selected individual in different coordinate system directions. This helps get accurate velocities of each individual.

Screenshots are taken every 10 seconds during the simulation until the tracked individual exits the corridor. Apply the process in section 3.1.2 and track three individuals at three different locations: one at the front of the crowd, one at the middle of the crowd, and one at the end of the crowd. Three methods in section 3.1.2 are applied to calculate densities for three tracked individuals. Method_1 is applied to the individual at the front of the crowd, Method_2 is applied to the individual at the middle, and Method_3 is applied to the individual at the end.

Results from applying different methods are summarized as Figure 3-15.

Time [s]	Method_1		Method_2		Method_3	
	Density pers/m2	Velocity m/s	Density pers/m2	Velocity m/s	Density pers/m2	Velocity m/s
10	1.25	1.189	0.97	1.19	1.31	0.51
20	1.33	1.189	1.24	1.19	1.44	0.58
30	1.7	1.19	1.44	1.19	1.52	1.19
40	1.89	1.19	1.46	1.19	1.52	0
50	2.68	1.19	1.5	1.19	1.54	0
60	2.72	1.19	1.86	1.19	1.68	1.19
70	3.06	1.19	1.98	1.19	1.72	1.19
80			2.12	1.19	1.79	1.19
90			2.45	0	1.99	1.19
100			2.88	0	2.04	1.19
110			2.98	0	2.09	1.19
120			3.03	0.32	2.19	1.19
130			3.22	0	2.35	0.08
140					3.31	0.47
150					3.43	0
160					4.35	0
170					4.79	0

Figure 3-15: All results from different density calculation methods.

In the results from the individual at the front of the crowd, velocity reaches 1.19 m/s while the density is 3.06 persons/m^2. This shows a big conflict with the speed-density correlation by Gwynne and Rosenbaum in the 5th edition of SFPE Handbook. [14] Because in the SFPE Handbook, densities higher than 0.56 persons/m^2 should have velocities lower than 1.19 m/s. Consequently, the density calculation method should not focus on calculating the density behind the selected individual.

Results from the persons at the middle and the end of the crowd are relatively reasonable. Velocities decreases when densities become larger than 2.45 persons/m^2. Maximum velocity (1.19 m/s) exists when densities are lower than 2.19 persons/m^2. Even though when densities are between 2 persons/m^2 and 2.19 persons/m^2, velocity is still 1.19 m/s, this can be caused by limited data.

Results in Figure 3-15 also show the disadvantages of the single person tracking method. The single person tracking method can only show one person's density at one time. It depends on the selected time point and total amount of data. When there is limited data, it may not be representative enough for the overall crowd.

In conclusion, the crowd around and in front of the occupant affect the occupant's density. Different density calculation methods can be applied for different occupant locations. When there are crowds in front of and behind the occupant, Method_2 should be applied. When there are few persons behind or in front of the occupant, Method_3 should be applied.

CHAPTER 4: VIDEO ANALYSIS

4.1 VIDEO SELECTION

Forschungszentrum Jülich, the national research institution located in Germany, conducts interdisciplinary research in the areas of energy, information, and bioeconomy. In Forschungszentrum Jülich, the Institute for Advanced Simulation (IAS) brings together simulation sciences and supercomputing. Under the IAS, the institute section of Civil Safety Research focuses on the scientific fields of pedestrian and fire dynamics. In this institute section, experimental and simulation data are shared to contribute towards a transparent scientific methodology. Experimental footage videos are found in the "Data Archive Of Experimental Data From Studies About Pedestrian Dynamics". [20], [21]

In the data archive, there are footage videos with different scenarios. Video recordings and resulting trajectories of individual pedestrians are available for most of the experiments. This helps to study the behaviors of each person.

As concluded in section 3.1.3, experiments conducted in a hallway are better choices for analysis data because it can provide more data with densities greater than 2 persons/m^2. Because of this, videos under the section "Corridor, unidirectional flow" are used for analysis.

There are nine videos included in this section. The frame rate of videos is 25 fps. Experiments with higher experiment number have more pedestrians, which results in a more dense crowd. In other words, Experiment_01 has the least number of occupants and the least dense crowd. By contrast, Experiment_09 has the largest number of occupants and the most dense crowd.

The setup of the corridor in the videos is shown as Figure 4-1.

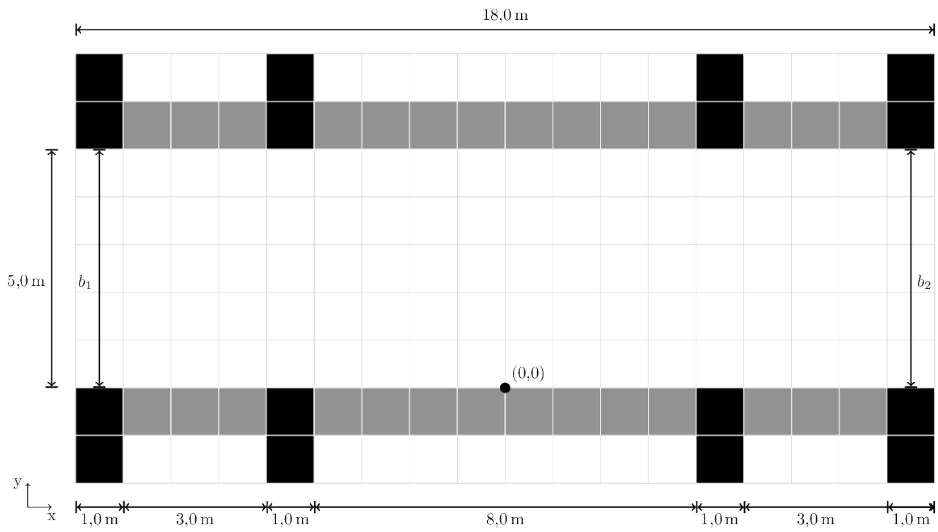

Figure 4-1: Corridor setup in the video section “Corridor, unidirectional flow”. [22]

The width of b_1, b_2 and moving direction are different between videos (shown as Figure 4-2).

Experiment	Direction	Width b1	Width b2
01	right to left	1.00	5.00
02	right to left	2.00	5.00
03	left to right	3.00	5.00
04	right to left	4.00	5.00
05	left to right	5.00	5.00
06	right to left	5.00	4.00
07	left to right	5.00	3.00
08	right to left	5.00	2.00
09	left to right	5.00	1.00

Figure 4-2: Width of b_1, b_2 and moving direction for each experiment. [22]

4.2 VIDEO ANALYSIS METHOD

This section introduces methods of extracting velocity and density data from footage videos. Because the view of videos is not symmetric at the corners (shown as Figure 4-3), video analysis tools are not used to process the videos. On the website, each video is provided with a trajectory document. The trajectories document provides X and Y coordinates of each person at each frame. Those trajectories documents are used to recreate video scenes for analysis.

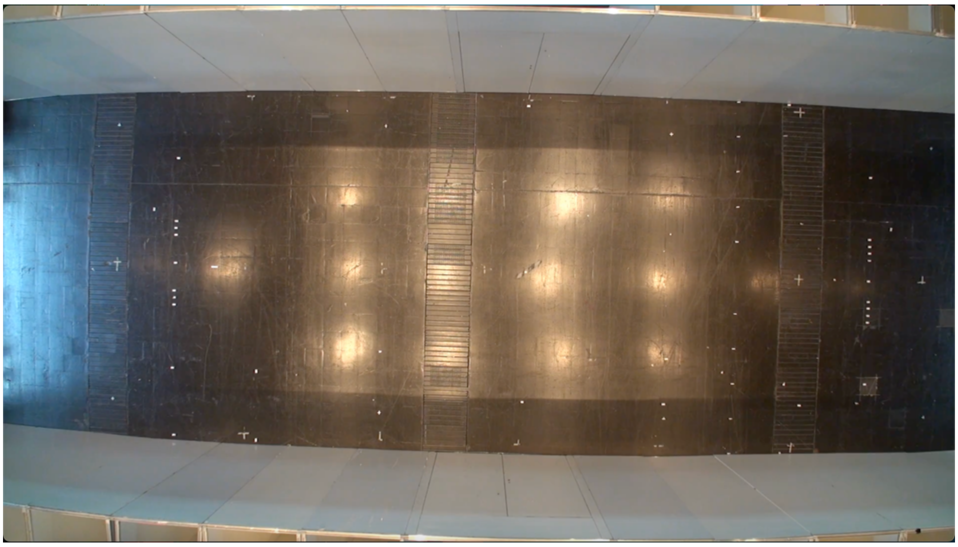

Figure 4-3: View of videos. [22]

4.2.1 RECREATE VIDEO SCENES IN SCATTERPLOTS

For each video, the resulting trajectories of pedestrians are available. The trajectories document includes the person's ID, frame, and X and Y coordinates. Since individual height is not considered an important parameter in the videos, the Z coordinate in the trajectories documents for all pedestrians is 1.76 m. Figure 4-4 is a part of one trajectories document:

# PersID	Frame	X	Y	Z
1	98	4.6012	1.8909	1.76
1	99	4.5359	1.8976	1.76
1	100	4.447	1.9304	1.76
1	101	4.3865	1.9364	1.76
1	102	4.3285	1.9452	1.76
1	103	4.2707	1.9487	1.76
1	104	4.2142	1.9536	1.76
1	105	4.1565	1.9545	1.76
1	106	4.0987	1.9554	1.76
1	107	4.032	1.9654	1.76
1	108	3.9787	1.9521	1.76
1	109	3.9223	1.9444	1.76
1	110	3.8395	1.9531	1.76
1	111	3.7832	1.9357	1.76
1	112	3.7154	1.9335	1.76
1	113	3.6433	1.9209	1.76

Figure 4-4: Example of trajectories. [22]

For each video, six pedestrians are randomly selected. For each pedestrian, frames when the pedestrian is moving in the corridor can be selected out. A start frame near the beginning of the video is randomly selected to start the analysis. All pedestrians located in the corridor at this start frame are noted. Next, a scatterplot at this frame can be created to recreate the crowd in the video. However, to avoid the effect of walls, if the selected pedestrian is plotted near a corridor wall, this pedestrian is not tracked and a new pedestrian is randomly chosen. Thus, most of the tracked pedestrians have Y coordinates between 1 to 4.

The following is an example of how to create a scatterplot at a specific frame. Pedestrian #68 in the video Experiment_01 is randomly chosen at Frame 975 (39 seconds in the video). All pedestrians walking in the corridor at 39 seconds and their coordinates are listed in Figure 4-5.

#	frame	x	y
60	975	-4.9395	0.4747
64	975	-4.8639	1.014
65	975	-0.5133	4.3655
66	975	-0.6742	3.246
67	975	-0.114	3.7702
68	975	-0.3184	1.9529
69	975	1.1462	3.5098
70	975	0.4425	0.9275
71	975	-4.0318	3.1621
72	975	2.0842	2.0734
73	975	2.6498	0.955
74	975	3.424	3.4262
75	975	-3.866	3.8946
76	975	-1.8029	1.3527
77	975	0.4614	1.5834
146	975	4.4839	1.6461

Figure 4-5: Trajectories of all pedestrians in the corridor at 39 seconds. [22]

The coordinates of all individuals in the frame are graphed in a scatterplot as Figure 4-6, with a red dot used to indicate pedestrian #68.

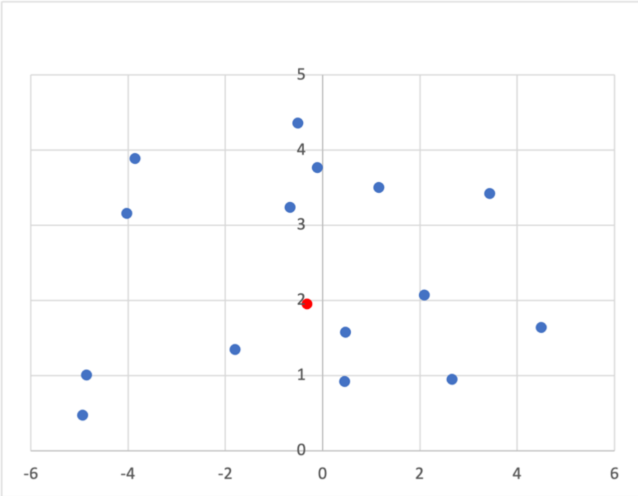

Figure 4-6: Scatterplot showing all pedestrians in the corridor.

A screenshot of the Experiment_01 video at 39 seconds is shown as Figure 4-7.

Figure 4-7: Picture of the Experiment_01 video at 39 seconds. [22]

Comparing Figure 4-6 to Figure 4-7, the number and location of dots in the scatterplot correctly match the pedestrians in the video. Since the diameter of dots does not indicate the shoulder width of pedestrians, the scatterplot looks less dense than the video scene.

4.2.2 VELOCITY CALCULATION WITH SCATTERPLOTS

For each selected pedestrian, a scatterplot is created every selected frame interval until the pedestrian exits the corridor. To make the velocity calculation effective, pedestrians should show some distance difference between two recorded frames, so the frame interval selected varies for different videos because of different dense levels. For more dense crowds, pedestrians move slower than pedestrians in less dense crowds. Thus, frame intervals for more dense crowds are longer than that for less dense crowds. Figure 4-8 is an example of frame interval in Experiment_07 and Experiment_08. The table of the complete frame interval selections for all videos can be found in Appendix A.

Experiment Number	PersID	Frame Interval	Time Interval [s]
07	768	200	8
	84	100	4
	272	200	8
	549	200	8
	21	50	2
	457	200	8
08	307	300	12
	323	300	12
	111	100	4
	318	300	12
	219	300	12
	438	300	12

Figure 4-8: Example of frame intervals in Experiment_07 and Experiment_08.

The distance that a pedestrian moves during one frame interval can be calculated using the coordinate change of the pedestrian. If a pedestrian's coordinate at Frame f_1 is (x_1, y_1), and the coordinates become (x_2, y_2) at Frame f_2, when $f_2 > f_1$, the time interval (t), distance (d), and velocity (v) can be calculated as:

$$t\ [s] = \frac{f_2 - f_1}{25\ fps} \quad 4\text{-}1$$

$$d\ [m] = \sqrt[2]{(x_2 - x_1)^2 - (y_2 - y_1)^2} \quad 4\text{-}2$$

$$v\ [m/s] = \frac{d}{t} \quad 4\text{-}3$$

This velocity is recorded at Frame f_2. There is no corresponding velocity for the start frame.

4.2.3 DENSITY CALCULATION WITH SCATTERPLOTS

The density calculation method follows the method described in section 3.4. When the pedestrian enters and is about to leave the video area, the density of people in front of the pedestrian is calculated. Only when the pedestrian is in the middle of the corridor, does the density calculation include people around the pedestrian rather than those just in front.

In a scatterplot, the meshes on the plot can help determine the area used for the density analysis. The number of people is counted in the selected area for analysis. If a dot is located on an edge of the calculation area, if half or more than half of the dot is within the area, the dot is counted. Otherwise, the dot is not counted.

Figure 4-9 and Figure 4-10 are the scatterplots for pedestrian #111 in Experiment_08 video at Frame 350 (14 seconds) and pedestrian #457 in Experiment_07 video at Frame 1800 (72 seconds). The red dot in the plot is pedestrian #111 and the calculation area is shown as the red box. In Figure 4-9, Pedestrian #111 is at the middle of the crowd, so Method_02 in section 3.1.2 is applied to locate the red box. In Figure 4-10, Pedestrian #457 is at the end of the crowd, so Method_03 is applied.

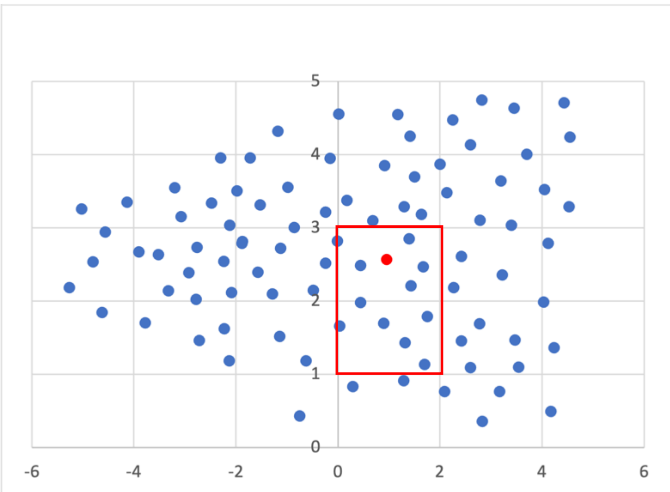

Figure 4-9: Scatterplot for pedestrian #111 in Experiment_08 video at Frame 350.

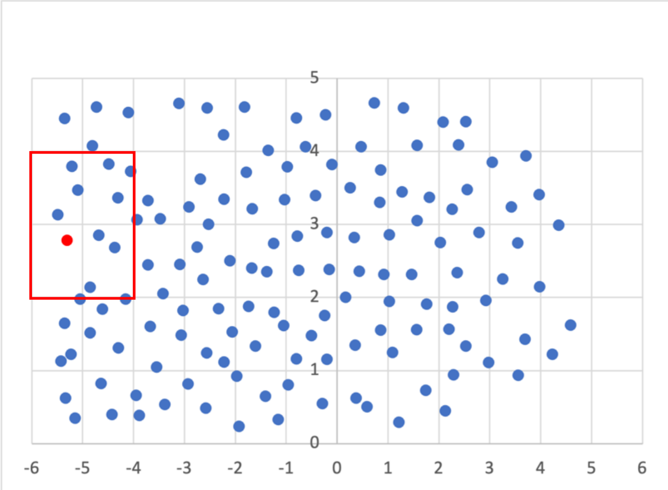

Figure 4-10: Scatterplot for pedestrian #457 in Experiment_07 video at Frame 1800.

For Pedestrian #111, the area (A), number of people (N), and density (D) in its calculation area are:

$$A = 2\,m \times 2\,m = 4\,m^2 \quad (4\text{-}4)$$

$$N = 12\ persons \quad (4\text{-}5)$$

$$D = \frac{N}{A} = \frac{12\ persons}{4\,m^2} = 3\ persons/m^2 \quad (4\text{-}6)$$

For Pedestrian #457, the area (A), number of people (N), and density (D) in its calculation area are:

$$A = 2\,m \times 2\,m = 4\,m^2 \quad (4\text{-}7)$$

$$N = 10\ persons \quad (4\text{-}8)$$

$$D = \frac{N}{A} = \frac{10\ persons}{4\,m^2} = 2.5\ persons/m^2 \quad (4\text{-}9)$$

If a density is calculated as D_1 at Frame f_1 and as D_2 at Frame f_2, when $f_2 > f_1$, the average of D_1 and D_2 is recorded as the density at Frame f_2. Because the velocity at Frame f_2 shows the movement from Frame f_1 to Frame f_2, this movement should correspond to the crowd flow behavior that happened between the two frames. The average of D_1 and D_2 can help show the average crowd flow behavior. Thus, the average density is recorded to match the velocity. Combined with the velocity calculation in section 4.2.2, the start frame does not have recorded velocity and density data.

4.3 VIDEO ANALYSIS RESULTS

As mentioned before, there are six tracked pedestrians for each video and there are a total of nine videos. When there are several velocity data with the same density, the average of all velocities with this density is recorded to create a one-to-one relationship between density and velocity. The organized density and velocity are shown as Figure 4-11. All of the data is summarized in the Appendix B.

Density [pers/m2]	Velocity [m/s]
0.25	1.46
0.375	1.49
0.5	1.45
0.625	1.34
0.75	1.16
0.875	1.13
1	1.10
1.125	1.04
1.25	1.10
1.375	1.02
1.5	0.89
1.625	0.91
1.75	0.73
1.875	0.81
2	0.69
2.125	0.67
2.25	0.64
2.375	0.62
2.5	0.61
2.625	0.43
2.75	0.30
2.875	0.43
3	0.35
3.125	0.24
3.25	0.21
3.375	0.23
3.5	0.19
3.625	0.29
3.75	0.15
3.875	0.14
4	0.05
4.125	0.30
4.25	0.09
4.375	0.08
4.5	0.06
4.625	0.06
4.75	0.01

Figure 4-11: Density and velocity results from video analysis.

Plot Figure 4-11 in MATLAB, it is shown as Figure 4-12:

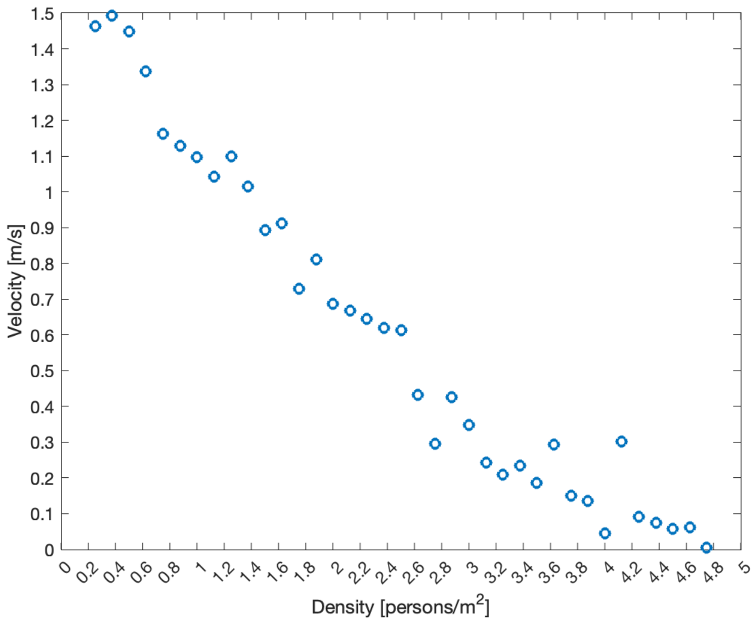

Figure 4-12: Density and velocity results plotted in MATLAB.

A fitting line can be generated in MATLAB based on the data. A fitting line equation is created as Equation 4-10, with a R-square value of 0.947.

$$v = -0.333D + 1.439 \qquad 4\text{-}10$$

where

v = speed in meter per second

D = density in persons per square meter

The speed-density correlation by Gwynne and Rosenbaum in the SFPE Handbook [14] can be plotted on the same graph with data in Figure 4-11 and the fitting line for comparison. It is plotted as Figure 4-13.

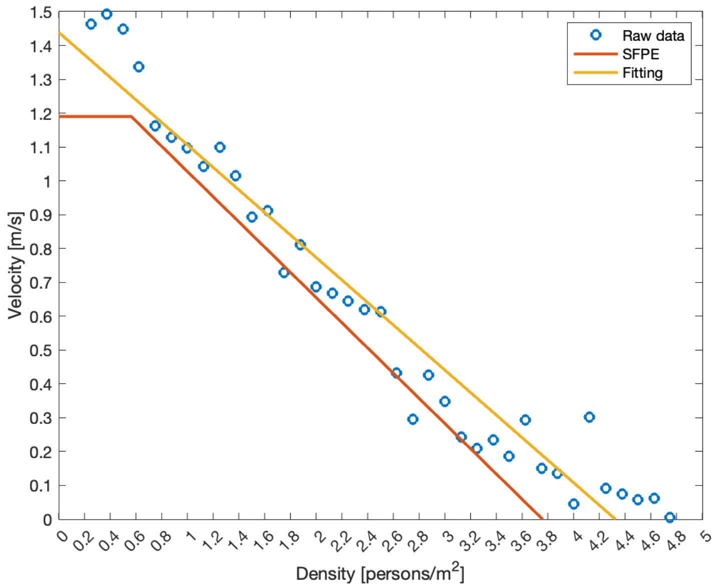

Figure 4-13: Comparison between the fitted curve and SFPE curve.

To compare the similarity between the SFPE curve and the fitted curve, Euclidean Distance is applied to calculate the distance between the two curves. Euclidean Distance between two points in one dimension is calculated with Equation 4-11. [23]

$$ED(a,b) = \sqrt{dist(a,b)}, dist(a,b) = (a_x - b_x)^2 + (a_y - b_y)^2 \qquad 4\text{-}11$$

To extend this method to two lines, let L_i and L_j be one-dimensional trajectory segments with n points, the equation above is converted to Equation 4-12.

$$ED(L_i, L_j) = \frac{1}{n}\sum_{i=1}^{n}\sqrt{dist(a_i, b_i)} \qquad 4\text{-}12$$

Using the Euclidean Distance to define the similarity, S, the relationship is shown as Equation 4-13.

$$S = \frac{1}{1 + ED(L_i, L_j)} \qquad 4\text{-}13$$

The range of S is [0, 1]. A greater S indicates a lower $ED(L_i, L_j)$, which means closer distance and more similarity between the two lines.

The distance between the SFPE curve and the fitting curve in a density range from 0 to

4.75 persons/m^2 is calculated using Equation 4-11 and 4-12. By applying Equation 4-13, the similarity, S, between the two curves is 0.90.

Because this research focuses on crowds with densities higher than 2 persons/m^2, the maximum velocity of 1.19 m/s from the SFPE Handbook can be kept. The fitting line equation is used for the part with velocities lower than 1.19 m/s and the new curve is shown as Figure 4-14.

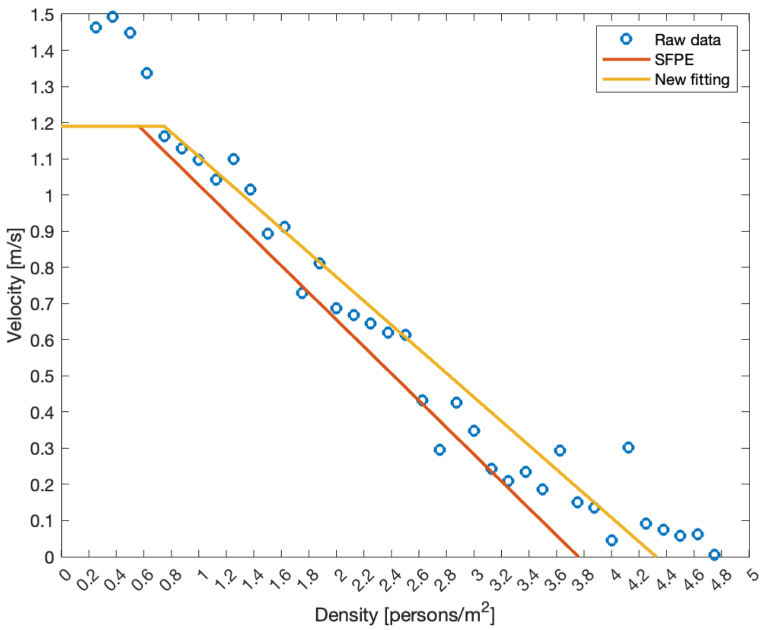

Figure 4-14: The new fitting curve with a maximum velocity of 1.19 m/s.

The speed-density relationship in Figure 4-14 is expressed as Equation 4-14.

$$v = 1.19\ {}^{m}/_{s} \qquad when\ D \leq 0.75\ {}^{persons}/_{m^2}$$

$$v = -0.3327D + 1.439 \qquad when\ D > 0.75\ {}^{persons}/_{m^2} \qquad 4\text{-}14$$

where

v = speed in m/sec

D = density in persons/m^2

CHAPTER 5: TESTING OF APPLICATIONS IN PATHFINDER

5.1 MODEL USED TO TEST

A test of the new density-velocity curve is conducted through an application of Pathfinder by simulating occupant movement in one of the experimental videos. The model is run with the new curve and the SFPE curve separately in Steering mode. Results are compared to discuss if the new curve better simulates crowd movement than the SFPE curve.

Because the new density-velocity curve focuses on improving the high-density part, the selected video should include high density crowds. As such, the scenario in Experiment_07 is modeled to test the application of the new density-velocity curve in Pathfinder. Both Experiment_08 and Experiment_09 include width changes of exits which alters the density of the pedestrians as they leave the corridor and hence is not useful when assessing the impact of the new speed-density curve.

5.2 MODEL SETUP

This section introduces details of modeling the scenario in Experiment_07. This includes a description of how the new density-velocity curve is imported into Pathfinder, geometry of the model and settings of other parameters.

5.2.1 APPLY THE NEW DENSITY-VELOCITY CURVE IN PATHFINDER

Pathfinder allows users to customize the speed of the occupant. In Edit Profiles, by choosing Advanced in Speed, it will open the Advanced Speed Properties dialog. Users can edit the Speed-Density Profile from table. In the Speed-Density Profile, speed is entered as a fraction of the occupant's maximum speed as a function of surrounding occupant density. In the new density-velocity curve, the maximum speed is 1.19 m/s, and the fraction is calculated using Equation 5-1. [17]

$$Speed\ fraction = \frac{v}{1.19\ ^{m}/_{s}} \qquad 5\text{-}1$$

where

v = speed in meter per second

Figure 5-1 is a screenshot from Pathfinder which shows the user interface of Speed-Density Profile. The entire speed fraction table is attached in Appendix C.

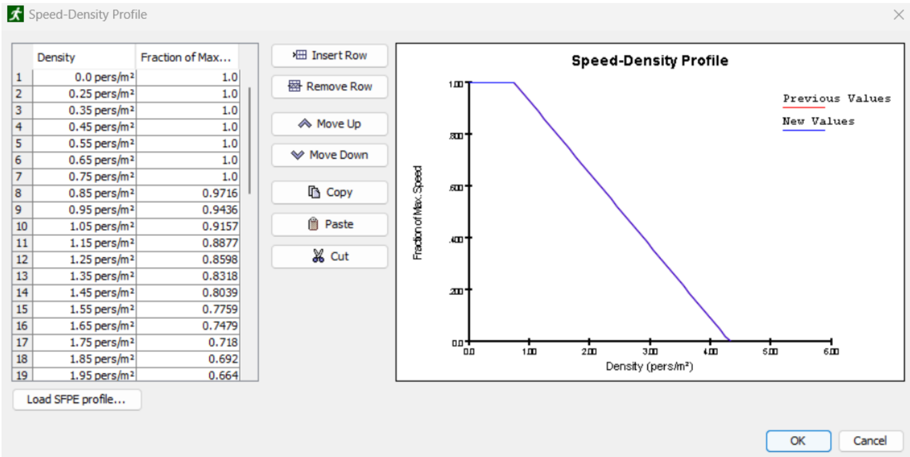

Figure 5-1: Screenshot of the user interface of Speed-Density Profile.

5.2.2 GEOMETRY AND PARAMETERS OF THE MODEL

According to Figure 4-2, pedestrians in Experiment_07 move from left to right. The corridor width is 5 m at the left side and 3 m at the right side. The total number of pedestrians is 914 as indicated in the trajectories document. The video does not show how much space pedestrians have before they enter the corridor. Rather than creating an artificial queue with a very high density with pedestrians overlapping each other, another 74 m by 5 m area is created at the left side of the corridor as a waiting area. 914 pedestrians are randomly distributed in this waiting area, creating a density of 2.49 persons/m^2 in this waiting area. One 2 m by 2 m measurement region is placed neat the exit. The entire model is shown as Figure 5-2.

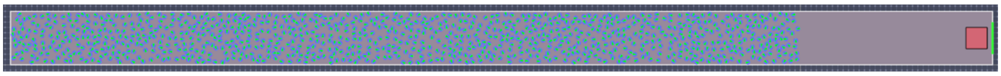

Figure 5-2: Test model based on Experiment_07.

The reduction factor, minimum shoulder width and acceleration time are enabled with default values, which are 0.7, 33 cm and 1.1 s respectively.

First, the new speed-density profile noted in section 5.2.1 is applied in the model and with the results saved in one folder. Then, the Speed-Density Profile is changed to the default SFPE correlation, the model is rerun, and the results saved in another folder.

5.3 RESULTS DISCUSSION

In the video of Experiment_07, it takes 209 seconds for all pedestrians to leave the corridor. With the new speed-density profile, Pathfinder gives an evacuation time of 198.8 seconds. With the SFPE correlation, the evacuation time is 235.3 seconds. Although applying the new speed-density profile provides a shorter evacuation time than the video time, it is still within 4.9% of the video time. The evacuation time from the SFPE correlation is within 12.6% of the video time. This shows that applying the new speed-density profile can provide a closer result to the experimental condition than the SFPE correlation.

To compare detailed results from the two models, screenshots are taken at 80 seconds of the simulation in the Debug mode. Figure 5-3 is the screenshot of the model with the new speed-density profile and Figure 5-4 is the screenshot of the model with the SFPE profile.

Figure 5-3: Model simulation at 80 s with the new speed-density profile.

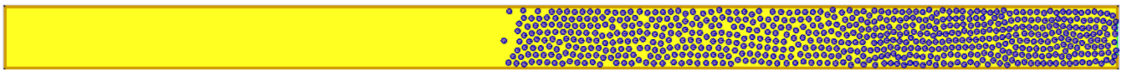

Figure 5-4: Model simulation at 80 s with the SFPE profile.

For each model, the single person tracking method described in section 3.3 is applied and five pedestrians along the horizontal centerline of the corridor are randomly selected to analyze the density around the selected pedestrian. Results from two models are summarized in Figure 5-5.

		Coordinates of selected points	Number of pedestrians	Length [cm]	Width [cm]	Area [m2]	Density [pers/m2]	Average density [pers/m2]
New correlation	Point 1	(8001.7, 328.95) (8114.7, 328.95) (8001.7, 194.98) (8114.7, 194.98)	4.5	113	133.97	1.51	2.97	3.07
	Point 2	(8557.3, 305.02) (8698.6, 305.02) (8557.3, 175.84) (8698.6, 175.84)	6	141.3	129.18	1.83	3.29	
	Point 3	(8792.7, 319.38) (8934.0, 319.38) (8792.7, 204.55) (8934.0, 204.55)	5	141.3	114.83	1.62	3.08	
	Point 4	(8190.1, 381.58) (8331.3, 381.58) (8190.1, 281.10) (8331.3, 281.10)	4	141.2	100.48	1.42	2.82	
	Point 5	(8773.9, 252.39) (8915.1, 252.39) (8773.9, 151.91) (8915.1, 151.91)	4.5	141.2	100.48	1.42	3.17	
SFPE correlation	Point 1	(7938.4, 324.16) (8060.6, 324.16) (7938.4, 209.33) (8060.6, 209.33)	4	122.2	114.83	1.40	2.85	2.86
	Point 2	(8680.8, 319.38) (8821.8, 319.38) (8680.8, 214.11) (8821.8, 214.11)	4.5	141	105.27	1.48	3.03	
	Point 3	(8849.9, 305.02) (8962.7, 305.02) (8849.9, 185.41) (8962.7, 185.41)	3.5	112.8	119.61	1.35	2.59	
	Point 4	(8267.3, 410.29) (8370.7, 410.29) (8267.3, 285.89) (8370.7, 285.89)	3.5	103.4	124.40	1.29	2.72	
	Point 5	(8925.1, 405.50) (9047.3, 405.50) (8925.1, 300.24) (9047.3, 300.24)	4	122.2	105.26	1.29	3.11	

Figure 5-5: Density comparison between two models.

The scatterplot of Experiment_07 at 80 s (2000 Frames) is used to determined densities associated with five randomly selected pedestrians along the horizontal centerline of the plot. Results from the scatterplot are summarized in Figure 5-6.

	Area [m2]	Number of pedestrians	Density [pers/m2]	Average density [pers/m2]
Point 1	4	13	3.25	3.05
Point 2				
Point 3				
Point 4		10	2.5	
Point 5		12	3	

Figure 5-6: Density from Experiment_07.

Comparing the average densities from Figure 5-5 and Figure 5-6, the average density from the model with the new correlation is higher than the average density from the video. While the average density from the model with the SFPE correlation is lower than the average density from the video. However, the average density with the new correlation is within 0.7% of the video average density while it is 6.2% with the SFPE correlation. This indicates that with the new correlation, the ability of models simulating details of flow behavior is improved.

On the other hand, velocity can be another parameter to assess. For each test, randomly select five pedestrians along the horizontal centerline of the corridor and record their velocities provided in the Debug mode. Same as above, using the scatterplot of Experiment_07 at 80 s, five pedestrians are also randomly selected along the horizontal centerline of the plot. Velocities of the selected pedestrians in the plot can be calculated using the same method mentioned in section 4.2.2. All velocities and the average velocity of each test is summarized as Figure 5-7.

	Velocity [m/s]		
	New correlation	**SFPE correlation**	**Video**
Point 1	0.27	0.41	0.27
Point 2	0.22	0.43	0.34
Point 3	0.30	0.40	0.23
Point 4	0.39	0.41	0.33
Point 5	0.44	0.32	0.39
Average velocity [m/s]	0.32	0.39	0.31

Figure 5-7: Velocity comparison between models and video.

Compare the average velocities in Figure 5-7, the average velocities from two models are higher than the average velocity from the video. The average velocity with the new correlation is within 3.3% of the video average velocity while it is 25.9% with the SFPE correlation. This result corresponds to the density assessment above. The new correlation improves the ability of models simulating crowd behavior with densities higher than 2 persons/m^2.

Figure 5-8 is a screenshot of Experiment_07 at 80 s.

Figure 5-8: A screenshot of Experiment_07 at 80 s. [22]

Compare Figure 5-3, Figure 5-4 and Figure 5-8, pedestrians in the model with the new speed-density profile are distributed randomly while it is uniformly distributed in the model with the SFPE correlation. In the screenshot of the video, it shows that pedestrians are randomly distributed without regularity, which is what happens in normal life. Therefore, the new speed-density profile can improve model's ability to indicate general lining habits of human.

CHAPTER 6: CONCLUSION

6.1 CONCLUSION

As mentioned before, this thesis attempts to develop a new speed-density relationship which focuses on crowds with densities greater than 2 persons/m^2. Using real world footage videos for analysis, this new speed-density relationship can provide human behaviors corresponds to normal life. The new speed-density correlation is concluded as Equation 4-14:

$$v = 1.19\ {}^{m}/_{s} \qquad\qquad when\ D \leq 0.75\ {}^{persons}/_{m^2}$$

$$v = -0.333D + 1.439 \qquad when\ D > 0.75\ {}^{persons}/_{m^2}$$

where

v = speed in m/sec

D = density in persons/m^2

This research also shows that Pathfinder can be applied to simulate high-density crowds. Advanced functions like reduction factor and acceleration time can help users to adjust crowd behavior according to their own needs. The Debug mode and measurement regions provide users with detailed simulation information.

By incorporating this new speed-density relationship with Pathfinder, the predictive ability of crowd simulation in the experimental conditions is improved per case examined. The predicted evacuation time from Pathfinder simulation is improved from 12.6% to within 4.9% of the experimental video time. The predicted flow density from Pathfinder is improved from 6.2% to within 0.7% of the average density from the experimental video. The predicted flow velocity from Pathfinder is improved from 25.9% to within 3.3% of the average velocity from the experimental video. Occupants in the model also behaves more closely to reality. With these improvements, models can better simulate crowd evacuation and help to reduce the number of casualties in future emergencies.

6.2 LIMITATIONS AND FUTURE WORK

There are many uncertainties related to human behavior. People's movements are generally unpredictable and can be influenced by their own internal personality traits. As a result, even in the same dangerous situation, their reactions can vary greatly. Additionally, humans possess strong social attributes that can affect their behavior. Their actions are often influenced by a combination of multiple factors, rather than a single factor. [8]

In this research, the new speed-density curve is applied to an experimental video to test its applicability. If the new curve can be tested with a real-world event video, like a video from a concert or a sports event, the applicability of the curve can be more representative. This is planned at the beginning of the research, but it is not successfully managed due to the time limit.

When a model is used to predict evacuation times, it is conservative that the evacuation time from the model is longer than the real-world evacuation time. One of the limitations of this research work is that it did not contain a wide range of data. Only nine videos and six pedestrians from each video were analyzed. The more data that is analyzed, the more generalizable the results will be. Shoulder width can also be one influencing factor. The default shoulder width in Pathfinder is 45.58 cm which is based on the average of measurements of male and female persons from nine countries [17], [24]. However, shoulder width may change because of different countries, ages, and genders. Explorations of acceleration time and measurement region were also limited. In different cases, occupants may accelerate faster or slower which corresponds to shorter or longer acceleration times respectively. Applications of measurement regions should also be determined based on the size and shape of modeled area. Thus, more combinations of parameters in Pathfinder are to be explored.

According to the current thesis, some additional research is recommended, as listed following:

- Test the applicability of the new speed-density curve with a real-world event video.
- Analyze footage videos with different sources and take more pedestrians into consideration.
- Explore the effects of gender, age, and nationality.
- Explore different values of parameters in Pathfinder in various scenarios.

APPENDIX A

Frame interval of all tracked pedestrians.

Experiment Number	PersID	Frame Interval	Time Interval [s]
01	68	50	2
	23	50	2
	76	50	2
	99	50	2
	49	50	2
	74	50	2
02	82	50	2
	726	50	2
	617	50	2
	507	50	2
	253	50	2
	380	50	2
03	905	50	2
	801	50	2
	828	50	2
	611	50	2
	330	50	2
	583	50	2
04	433	50	2
	891	100	4
	180	50	2
	606	50	2
	85	50	2
	57	50	2
05	187	100	4
	794	100	4
	97	100	4
	604	100	4
	302	100	4
	452	100	4

Experiment Number	PersID	Frame Interval	Time Interval [s]
06	172	100	4
	90	100	4
	901	100	4
	609	100	4
	304	100	4
	450	100	4
07	768	200	8
	84	100	4
	272	200	8
	549	200	8
	21	50	2
	457	200	8
08	307	300	12
	323	300	12
	111	100	4
	318	300	12
	219	300	12
	438	300	12
09	190	200	8
	307	200	8
	122	200	8
	203	200	8
	100	200	8
	155	200	8

APPENDIX B

All speed density data from video analysis

Density [pers/m2]	Velocity [m/s]	Average Velocity [m/s]
0.25	1.41 1.52 1.46	1.463333333
0.375	1.44 1.41 1.5 1.62	1.4925
0.5	1.725 1.545 1.635 1.385 1.3 1.105	1.449166667
0.625	1.33 1.54 1.46 1.165 1.185	1.336
0.75	1.355 0.915 1.22	1.163333333
0.875	1.37 1.205 1.035 1.1 1.045 1.33 0.82	1.129285714
1	1.26 0.935	1.0975
1.125	1.1 1.065 1.25 0.865 0.795 1.095 1.12	1.041428571

Density [pers/m2]	**Velocity [m/s]**	**Average Velocity [m/s]**
1.25	1.115	1.0995
	1.22	
	1.015	
	1.03	
	1.1175	
1.375	1.025	1.015
	0.885	
	1.315	
	0.835	
1.5	1.205	0.892857143
	1.11	
	0.87	
	0.76	
	0.705	
	0.855	
	0.745	
1.625	0.955	0.9125
	0.715	
	0.985	
	0.995	
1.75	0.875	0.73
	0.75	
	0.835	
	0.835	
	0.82	
	0.4125	
	0.525	
	0.475	
	0.495	
	1.085	
	1.01	
	0.92	
	0.51	
	0.5875	
	0.815	

Density [pers/m2]	Velocity [m/s]	Average Velocity [m/s]
1.875	0.705	0.811388889
	0.945	
	0.745	
	0.45	
	0.895	
	0.675	
	1.025	
	0.8125	
	1.05	
2	0.86	0.68775
	0.73	
	0.715	
	0.75	
	0.82	
	0.745	
	0.65	
	0.525	
	0.57	
	0.5125	
2.125	0.79	0.6675
	0.79	
	0.61	
	0.52	
	0.78	
	0.515	
2.25	0.49	0.644375
	1.1425	
	0.45	
	0.5525	
	0.6325	
	0.9275	
	0.49	
	0.47	
2.375	0.7	0.619916667
	0.675	
	0.565	
	0.79	
	0.6625	
	0.4675	
	0.69	
	0.8375	
	0.5125	
	0.595	
	0.31875	
	1.105	
	0.8	
	0.11625	
	0.46375	

Density [pers/m2]	Velocity [m/s]	Average Velocity [m/s]
2.5	0.4825	0.613295455
	0.97	
	0.475	
	0.4775	
	0.495	
	0.5075	
	0.8175	
	1.085	
	0.975	
	0.3275	
	0.13375	
2.625	0.56	0.43145
	0.3925	
	0.3875	
	0.3858	
2.75	0.4475	0.296428571
	0.3525	
	0.415	
	0.3	
	0.10375	
	0.28625	
	0.17	
2.875	0.465	0.4255
	0.4725	
	0.7025	
	0.2325	
	0.255	
3	0.465	0.34755625
	0.5225	
	0.425	
	0.34875	
	0.435	
	0.31625	
	0.2117	
	0.05625	
3.125	0.5475	0.243125
	0.11875	
	0.0875	
	0.21875	
3.25	0.29375	0.209171429
	0.3125	
	0.4075	
	0.2192	
	0.01875	
	0.10625	
	0.10625	

Density [pers/m2]	Velocity [m/s]	Average Velocity [m/s]
3.375	0.33375 0.2058 0.2142 0.1858	0.2348875
3.5	0.2925 0.08	0.18625
3.625	0.3475 0.57 0.2067 0.0475	0.292925
3.75	0.25 0.115 0.11875 0.115	0.1496875
3.875	0.1983 0.1983 0.1375 0.0075	0.1354
4	0.045	0.045
4.125	0.4075 0.1958	0.30165
4.25	0.09125	0.09125
4.375	0.0542 0.09625	0.075225
4.5	0.0017 0.0608 0.10875	0.057083333
4.625	0.005 0.1125 0.1075 0.025	0.0625
4.75	0.00625	0.00625

APPENDIX C

All speed fractions.

Density[persons/m2]	Speed fraction
0	1.0
0.25	1.0
0.35	1.0
0.45	1.0
0.55	1.0
0.65	1.0
0.75	1.0
0.85	0.9716
0.95	0.9436
1.05	0.9157
1.15	0.8877
1.25	0.8598
1.35	0.8318
1.45	0.8039
1.55	0.7759
1.65	0.7479
1.75	0.7180
1.85	0.6920
1.95	0.6640
2.05	0.6361
2.15	0.6081
2.25	0.5802
2.35	0.5522

Density[persons/m2]	Speed fraction
2.45	0.5243
2.55	0.4963
2.65	0.4684
2.75	0.4404
2.85	0.4124
2.95	0.3845
3.05	0.3565
3.15	0.3286
3.25	0.3006
3.35	0.2727
3.45	0.2447
3.55	0.2167
3.65	0.1888
3.75	0.1608
3.85	0.1329
3.95	0.1049
4.05	0.0769
4.15	0.0490
4.25	0.0210
4.35	0.0
4.45	0.0
4.55	0.0
4.65	0.0
4.75	0.0

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