AN ABSTRACT OF THE THESIS OF

Yue Xu for the degree of Master of Science in Civil Engineering

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Haizhong Wang

Increasingly congested surface transportation network in urban areas and growing land values make underground transportation systems more attractive for highways (i.e., tunnels) and metro system compared to other options [1]. An underground transportation system can preserve the land above for recreational parks, commercial buildings, residential homes, or other purposes while providing an efficient, cost-effective underground corridor to move people and goods by separating from the surface system [1]. However, the underground transportation systems present safety and operational challenges as well if incidents (e.g., fire, flood, terrorist attacks) occur. Major tunnel incidents since 1995 have killed 713 people worldwide [1]. From 1999 to 2001, several tunnel fires with multiple deaths occurred in Europe. For example, 39 people died in the fire in the Mont Blanc Tunnel between France and Italy in March 1999, 12 people died in the fire in the Tauern Tunnel in Austria in May 1999, and 11 people died in the fire in the Gotthard Tunnel in Switzerland in October 2001 in which the temperature reached 1,000 degrees Celsius (°C) (1,832 degrees Fahrenheit (°F)) within a few minutes [1]. These incidents caused significant safety concerns regarding underground transportation system safety. This problem is complex for

multiple reasons: (1) how people will react in tunnel emergencies is unpredictable, (2) fixed entrances and exits, (3) evacuation is likely to be self-initiated, (4) high-density presence of pedestrians, and (5) difficult to access for first responders and emergency vehicles.

The objective of this thesis is to present an interdisciplinary agent-based evacuation modeling framework for emergencies in underground transportation systems. Through this established framework, we will identify and validate the critical factors which affect life safety in underground emergency scenarios. The identification of the critical factors is validated by empirical data from historic underground tunnel accidents. The evacuation model is built through an agent-based platform: Anylogic. Then, a multi-discipline framework is introduced to analyse and identify problems related to evacuation in underground transportation systems. Finally, we study in detail and simulate the effects of ticket gate type, walking speed, gender, group size, pedestrian's density, and smoke on evacuation time. The research results from this thesis will provide decision-making support and guidance for government decision-makers, design engineers, and agency professionals to optimize underground station design. The experiment results indicate that the proposed agent-based underground transportation emergency evacuation modeling framework in this thesis is effective at evaluating the impacts of the identified critical factors on evacuation efficiency and life safety.

An Agent-based Evacuation Modeling of Underground Fire Emergency

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APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Yue Xu, Author

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1. INTRODUCTION

As modern cities develop, underground transportation has been playing a critical role in big cities. According to statistics from International Association of Public Transport (UITP) [2], 148 cities around the world own metro systems, totally approximately 540 lines as of 2014. Together, they carry over 150 million passengers per day (See Figure 1.1). By the end of 2015, there are already 110 metro lines in 27 cities and the total length of the operating lines reached 3375.9 km in China according to the statistics from Urban Rail Transit Research [20]. Underground transportation systems enjoy the advantages of larger capacity, higher speed and relatively lower ticket price. An increasing number of people choose underground transportation system as their preferred mode to commute. According to a survey in Beijing, average daily traffic volume in the Beijing Subway is 9,326 thousand people per day, which is relatively higher than other cities in China [21]. Figure 1.2 shows the pedestrian flow during peak hours in one of subway stations in Beijing [3].

1.1. Problem Definition

High-density traffic and overly crowded situations present safety and operation challenges in underground transportation system for system operators. It is often difficult for people to navigate high-density pedestrian flow in underground transportation

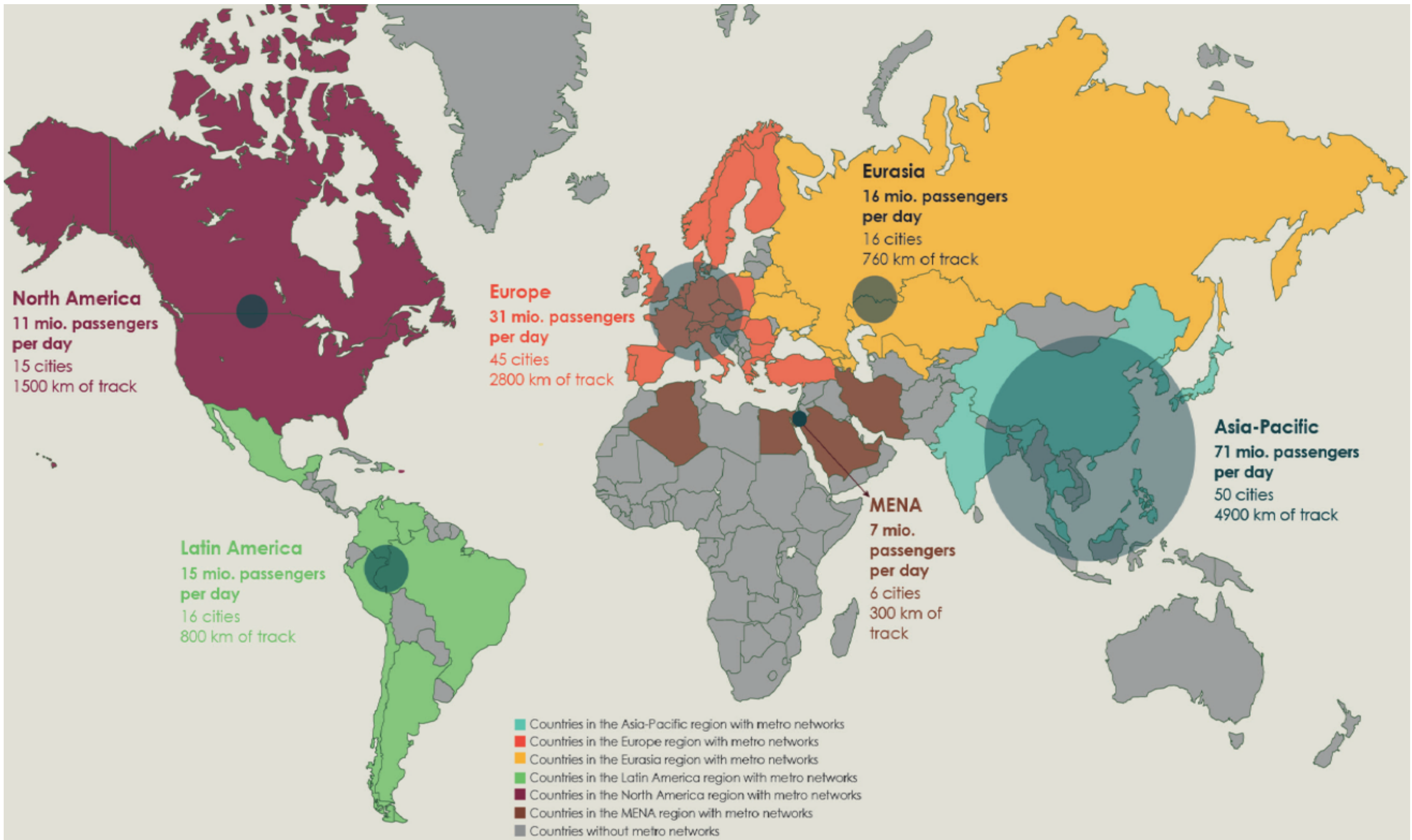


FIGURE 1.1: Metro System in World Map [2]

(a) High-density Pedestrian flow in train

(b) High-density Pedestrian flow in subway station

FIGURE 1.2: High-density Pedestrian Flow in Underground Transportation System in Beijing [3]

systems at normal peak hours. Compared to other surface public transportation systems such as buses, underground transportation systems have relatively limited space and accessibility when incidents occur, especially because these systems are confined to fixed entrances and exits. Depending on the nature of the hazards (e.g., type, magnitude, and duration), the evacuation from underground systems is often self-initiated with or without correct information to guide system users. Consequently, the casualty and injury are likely to be severe if there is no evacuation plans in place. Major accidents have occurred around the world in previous years. For example, on November 18, 1987, a fire started in a wooden escalator at King's Cross station in London, which led to 31 fatalities and more than 100 injuries [18]. 84 people were killed in Paris subway fire in 1903 [22]. In the Daegu city, South Korea subway station in 2003, the casualties reached to 138 and 99 people were reported missing during the fire emergency [23]. On October 28, 1995, a fire broke out in Baku's subway, at least 289 people were killed and 265 people injured in the capital of Azerbaijan [24]. Figure 1.3 shows how severe these disasters are in underground transportation system. More empirical accidents will be summarized in the next chapter. Therefore, it is imperative to identify and measure the impacts of those critical factors which affect life safety in underground transportation emergencies.

1.2. Significance

With the rapid development of economy and urbanization, urban population increase dramatically which drives the higher demand for underground transportation systems. Based on the statistic from UITP, Figure 1.4 shows the current estimates of the total length of metro lines by 2025 [4]. As mentioned above, high-density pedestrian flow, limited available space, fixed entrance and exit in underground transporta-

(a) Fire accident in King's Cross (London, UK, 1987) [25]

(b) Fire accident in Paris Metro (Paris, France, 1903) [26]

(c) Fire accident in Baku Metro (Baku, Azerbaijan, 1995) [27]

(d) Fire accident in Subway(Daegu, South Kerea, 2003) [28]

FIGURE 1.3: Fire Accidents in Underground Transportation System

tion systems present unique challenges for underground emergency response. Hence, research is urgently needed about how to react to and deal with these accidents and emergencies. Although previous scholars have conducted a great amount of research on underground emergency evacuation, further research is necessary. For example, precaution should be highly considered during the early stage of subway construction. What's more, it is very difficult to change the infrastructure once the subway is established. When these accidents happen, high-efficient evacuation tends to be the best approach to minimize the loss. However, previous research on accidents ignore a key factor which may significantly affect the evacuation. For instance, Kisko and Francis [29]'s model and Takahashi [30]'s model ignored human interaction by considering evacuees as an integer [5]. But actually, in most situation, an accident can not just be explained by only one factor. Multiple reasons, such as human factors, different hazard types, and infrastructure features should be considered together. Therefore, it is of great significance to developing a multidisciplinary framework considering various evacuation factors to achieve effective evacuations during an underground emergency.

1.3. Objective and Motivation

The purpose of this thesis is to analyze several critical factors that affect the evacuation time in an underground system emergency. Underground transportation systems own the unique features from other public transportation systems, such as high density pedestrians flow, limited available space and fixed entrance and exit, which make it difficult to evacuate. However, the previous research on this topic might be not suitable for the current situation. Therefore, a interdisciplinary framework is presented to analyse and to identify problems related to evacuation in underground transportation systems. The evacuation process is simulated by using an agent-based

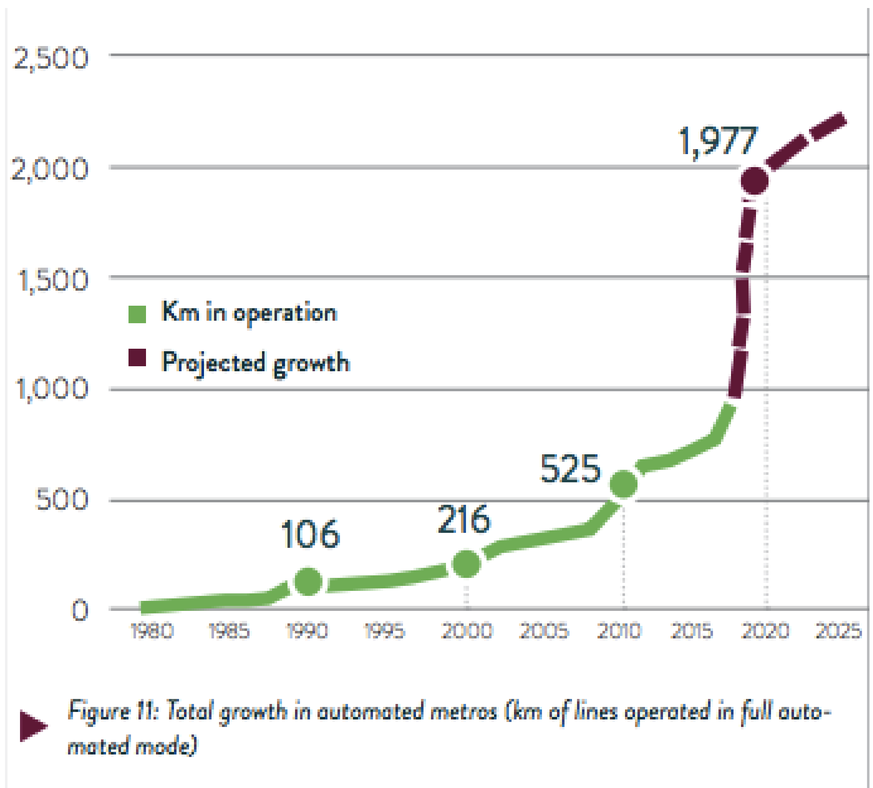


FIGURE 1.4: Total growth in Metro System (km of line length) [4]

model in Anylogic. The effects of ticket gate type, walking speed, gender, group size, pedestrian density, and smoke on evacuation time are studied and simulated in detail by a case study. The research results from this thesis provide some valuable information and guidance for decision makers to optimize underground station design. Additionally, this result can improve the efficiency of evacuation with more factors considered. Furthermore, it can minimize fatalities and reduce economic loss caused by underground emergency.

1.4. Thesis Organization

This thesis begins with a literature review about past underground emergency history and key factors affecting evacuation time and pedestrian modelling in underground transportation systems in section 2. Section 3 presents a interdisciplinary framework and a methodology to achieve the desired outcomes, along with the introduction of agent-based modeling and the tool called Anylogic used in the simulation process. Assumptions and parameter setup are discussed as well. Then second 4 introduces the result and discussion based on the former evacuation simulation. In this section, the simulation results related to the key factors mentioned in section 3 are described. Finally, conclusions and future study are presented in section 5. According to the results, this thesis concludes several major findings which summarize the research and also provided several future studies which can minimize the fatalities and reduce economic loss caused by the underground emergency.

2. LITERATURE REVIEW

This section aims to review and summarize the existing literature related to emergencies in underground transportation system and analyze the unique characteristics of fire emergency. Then, we identify several critical factors which affect the evacuation time and life safety outcome in underground transportation systems. The studied literature can roughly be divided into three categories: (1) different types of empirical accident in underground transportation system; (2) the characteristics of fire accidents; and (3) identification of critical factors and the major models for escaping pedestrian.

2.1. Summary of Empirical Accidents

This section presents a review of the empirical emergency accidents occurred in underground transportation system. The goal of this review is to learn from what happened in the past regarding what worked or not. According to Fridolf [18], a list of major accidents in underground transportation is summarized in Table 2.1 in terms of the number of fatalities and injuries, the cause of fire accidents, and the type of hazards. Table 2.1 is summarized based on the different hazard types.

As presented in Table 2.1, it is worth noting that most underground accidents happened are associated with fire emergency. The actual causes of the fire accidents vary, but the consequences (fatalities or injuries) are often severe because of the high temperature and smoke generated, for example, the fire in King's Cross in 1987 [18]. Most people have not experienced this type of life-threatening situations before, therefore, they are not educated regarding how to react to this emergent condition and what

TABLE 2.1: A summary of empirical subway accidents (Row 2 to Row 9 are from Fridolf [18]'s summary)

Year	Location	Cause	Outcome #fatalities/#injuries	Hazard Type
1987	King's Cross	Escalator ignited by a match	31/-	Fire
1991	Zurich	Arsonist setting one of the trains on fire	0/0	Fire
1995	Baku	An electrical failure cause a fire	289/265	Fire
1999	Mont Blanc	A fire staring in a truck cab inside the tunnel	39/-	Fire
2000	Kaprun	Overheating in a electrical fan	155/-	Fire
2003	Daegu	Arsonist starting a fire in a train at the station	189/150	Fire
2005	Rinkeby	An electrical failure causing a fire in a train	0/12	Fire
2007	Burnley	An collision including three trucks and five cars	3/0	Fire
1995	Tokyo	Five people launched a chemical attack [31]	12/50	Human
2000	Moscow	A explosion in subway tunnel [32]	13/90	Human
1995	Toronto	Human error and design flaw [33]	3/30	Human
2013	New York City	The train runs off its rails [34]	4/61	Human
2001	Taipei	Typhoon cause serious flood [35]	0/0	Water flood
2011	Shanghai	A running train crashed into a stalled train [36]	0/271	Signal Failure
2009	Washington, DC	A moving train collided with a train stopped ahead [37]	9/80	Electricity

are the correct course of actions to follow. In addition, people tend to be more panic than usual in fire-related emergencies [38]. The evacuation is very likely to be self-initiated with prevalent uncertainties. While in the 1995 Baku Metro fire [18], people noticed the fire and tried to evacuate. But it turned out that the ventilation system was switched to exhaust mode and the smoke was in the direction of evacuation. A lot of people died of being suffocated. Compared to other types of hazards, fire accidents in underground transportation system have distinguishing characteristics.

- High density pedestrian flow, limited space and fixed entrance and exit present unique challenges in underground transportation system when accident happens [39].
- Shields [40] points out that most people considered tunnels as complex structures, which means this perceived complexity will strengthen the difficulty of an emergency evacuation.
- Once fire emergency happens, correspondingly, smoke spreads very quickly compared to pedestrian's walking speed. Hu et al. [41] concluded that the average longitudinal velocity of smoke was roughly 1.8 to 2.3 m/s while desired walking speed for pedestrian crowds is 1.34 m/s [42]. Meanwhile, it is very difficult to dissipate the smoke in the limited and narrow space, like underground transportation system. With the temperature getting higher, the spread will be quicker, which makes the situation worse.
- Fire accidents can cause consecutive consequence and disasters. Tsukahara et al. [43] pointed out that evacuees tend to suffer the most physical damage during fire emergency. For example, smoke contains several toxic gases: carbon monoxide (CO), carbon dioxide (CO^2), chlorine, and hydrogen cyanide, which

can make pedestrian poisoned. Moreover, high density smoke quickly leads to indoor visibility decreased, which brings panic to people and increases the difficulty of evacuation [13].

- The difficulty of underground evacuation is relatively higher compared to other evacuation. Once the fire emergency happens in the underground construction, the lighting power will be cut off and the inside space become dark. When the visibility is impaired, the pedestrian walking speed is reduced [18]. The fire incident happened in the Zürich Metro is an example. The outside rescue was provided by the handrails, however, pedestrian didn't use it because of the low visibility [44].

Therefore, to comprehensively analyse problems related to fire evacuation in underground transportation systems and improve the safety in underground transportation systems, critical factors which can affect evacuation outcome should be thoroughly and deeply considered. In the following section, critical factors affect the evacuation time in underground transportation systems and main pedestrian models will be reviewed.

2.2. Critical Factors Affect the Evacuation Time

2.2.1 Human Factor

Human behavior in disaster is generally unpredictable. We review the following aspects of the human factors in emergency: psychological conditions, decision-making time, walking speed, group behavior and pedestrian density.

2.2.11 Psychological Condition

People are likely to be panic and have disordered behaviors in response to unfamiliar situations, which may lead to serious serial incidents. For evacuation modeling, human factors and their impacts on life safety are crucial considerations to create more realistic evacuation models. When accidents happen, people tend to communicate with others to figure out what is going on. The panic would spread from one person to the other. The mixed emotion of panic and scare would affect the pedestrian's judgment and behavior. These factors include sex, age, education background, safety education and life experience. Wang [19] used the panic scale and questionnaire to determine the weight coefficients which affected human behavior (See Table 2.2). Zhao and Tang [12] mentioned that people tend to fluster if they were in the environment where had poor visibility, smog and other unexpected occurrence. "Herding behavior"was provided by Helbing et al. [6]. It is to transmit control from one person to another, which might cause overcrowding and slower escape. Caliendo et al. [45] pointed out that pedestrian's behavior was affected by other people so they could follow other people's decision.

TABLE 2.2: Weight Values of the Affecting Factors [19]

Panic level affecting level	Age	Carrying luggage	Safety education level	Evacuation experience	Density	Environment	location of the fire
Weight Values	0.092	0.132	0.24	0.324	0.346	0.451	0.321

2.2.12 Decision-making Time

When disaster occurs, the realization of a danger and a threat is crucial for improving the efficiency of evacuation [46]. Shang and Li [36] pointed out that the reaction time mainly depended on the features of construction, the level of perfection and the building alarm system. Haack and Schreyer [47] stated that the reaction time could be very different depending on the different situation. Proulx [48] presented that the evacuee's position will affect their reaction time. Kohl et al. [11] also assumed decision time (reaction time) is 2 minutes for all scenarios if the communication sequence is well designed. Zhong et al. [5] used the Figure 2.1 to illustrate their definition of reaction time (perception time). In Korhonen et al. [49]'s simulation, the reaction time was modelled by a normal distribution with a standard deviation of 15 s and mean 60 s.

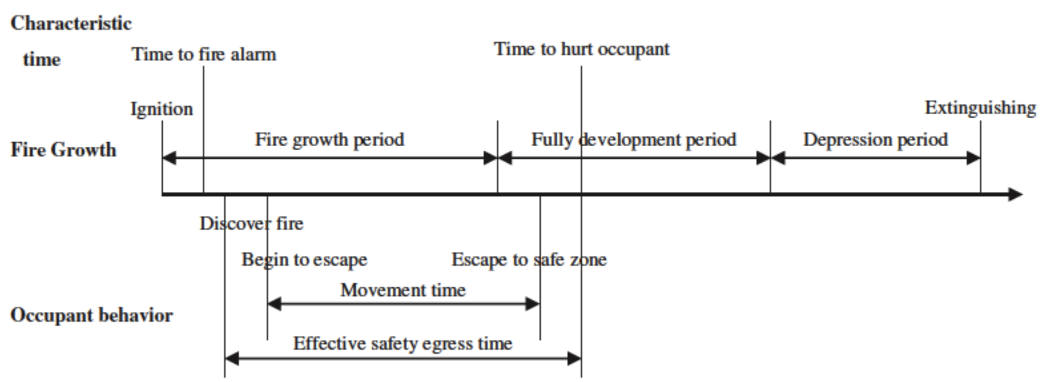


FIGURE 2.1: Occupant evacuation criteria in fire safety engineering level[5]

2.2.13 Walking Speed

For walking speed, Helbing et al. [6] explored that the relationship between the leave time for 200 pedestrians and the walking speed, and found out that under normal situation, the leave time decreases with speed growing. But when the desired velocities were higher than 1.5 m/s, it would reduce the efficiency of leaving and the clogging situation will form (See Figure 2.2). Kohl et al. [11] suggested that there were two types of walking speeds. One was walking speed on the platform and the other was walking speeds on solid stairs. They concluded that an average walking speed was 1 m/s for calculating the evacuation. While on solid stairs, the walking speed related to the vertical height components of the stairs was 0.25 m/s. Lei et al. [7] use the Table 2.3 to illustrate that walking speed can be divided into five categories by using approach about the body moving speed and diameter distributions: Child, Adult, Male, Female and Elderly (See Figure 2.3).

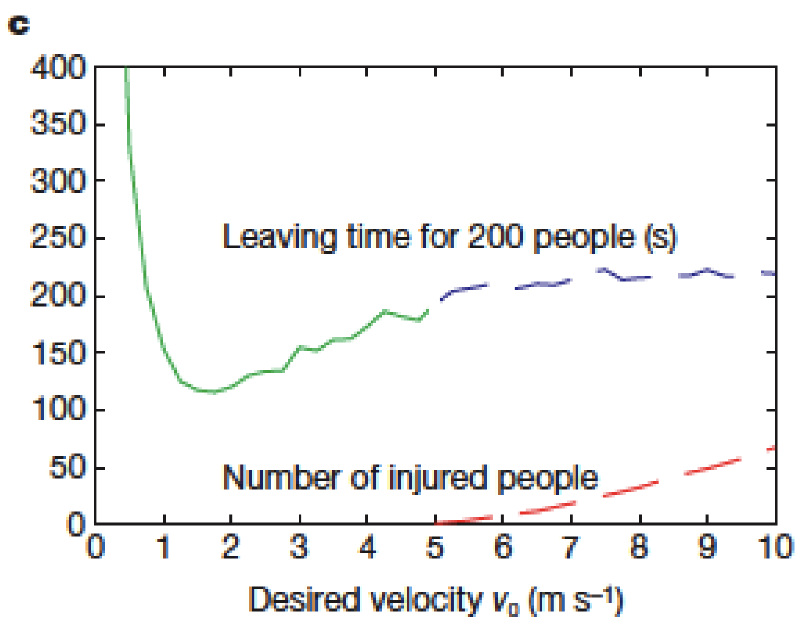


FIGURE 2.2: The relationship between the leave time for 200 pedestrians and the walking speed[6]

TABLE 2.3: Body dimensions and unimpeded walking velocities in FDS + Evac [7]

Body Type	Rd(m)	Rs/Rd(-)	ds/Rd(-)	Rt/Rd(-)	Speed(m/s)
Child	0.210±0.15	0.3333	0.6667	0.5714	0.90±0.30
Adult	0.255±0.035	0.3725	0.6275	0.5882	1.25±0.3
Male	0.270±0.020	0.3704	0.6296	0.5926	1.35±0.2
Female	0.240±0.020	0.3750	0.6250	0.5833	1.15±0.2
Elderly	0.250±0.020	0.360	0.6400	0.6000	0.8±0.3

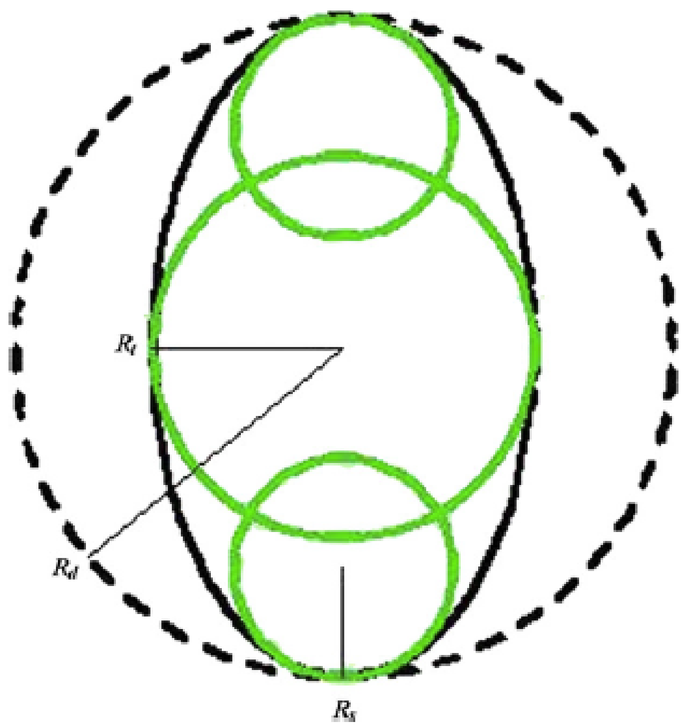


FIGURE 2.3: Illustration of the human body approximated by a combination of three overlapping circles.[7]

2.2.14 Group Behavior and Group Size

Group behavior mainly focus focuses on the behavior of the small group, which is including affiliation, leadership, trust, helping behavior [46]. These group behavior is largely related to the efficiency of the evacuation [46]. Moussaid et al. [8] reported that communication and social interaction between group members could significantly affect the crowd dynamics. Moussaid et al. [8] also indicate that group size has a significant effect on several valuable parameters during evacuation. Based on the empirical results, the walking speeds decrease when group size are increasing for both density levels (See Figure 2.4).

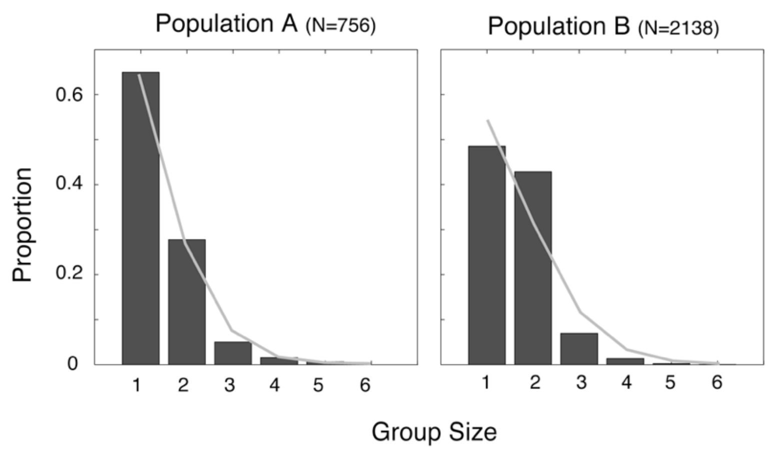


FIGURE 2.4: The relationship between walking speed and group size in different density level[8]

Gates et al. [9] also agree this conclusion: group size has a negative relationship on the walking speed. But they also mention that group size divided into three categories: individual, groups with two to four people, and groups with five or more. After testing, they proved the relationship between 95% confidence interval of walking speed and group size, which was presented in the Figure 2.6.

Moussaid et al. [8] give two equations explaining the effects of group size on

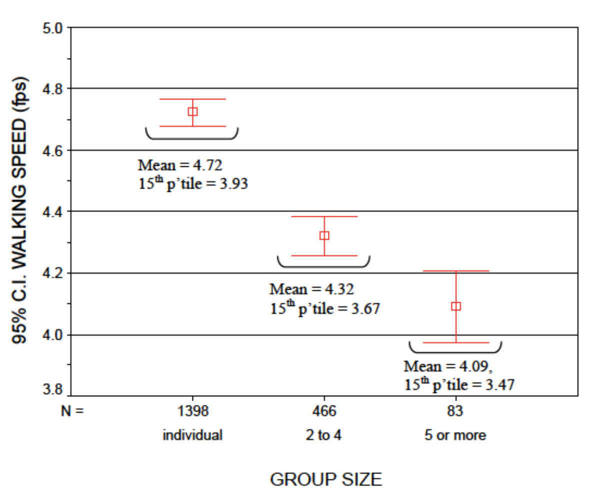


FIGURE 2.5: The relationship between 95% CI of walking speed and group size[9]

walking speed at two density levels.

$$y = \begin{cases} -0.04x + 1.26 & LowDensity \\ \\ -0.08x + 1.24 & HighDensity \end{cases} \tag{2.1}$$

where:

x : Group size(number of persons)

y : Walking speed(m/s)

Tarawneh [50] also agreed this conclusion by collecting 3500 pedestrian's walking speed at 27 crosswalks. He explained that pedestrian in larger group tend to talk with each other, which might reduce their walking speed.

2.2.15 Effects of Pedestrian's Density

Pedestrian density can affect human psychology and the efficiency of evacuation as well. Fruin [51] presented that when the density of people was nearly 4 person/m^2, it was a crowd situation, which had certain influence on psychological state. Cheng and Yang [3] also pointed out that the density of pedestrian flow under emergency was much higher compared to normal situation. Higher density of pedestrian flow will lead to lower evacuating speed and serious congestion problem during evacuation. To quantify the relationship between density and evacuation, Lei et al. [7] took occupant densities of 0.2, 0.3, 0.4, 0.6, 0.9, 1.3, 1.9, 2.7, 4.0 person/m^2 respectively to simulate the pedestrian crowds' evacuation. Then they found out that the higher the density, the longer the evacuation time. Figure 2.6 shows the relationship between walking speed and crowd density [10].

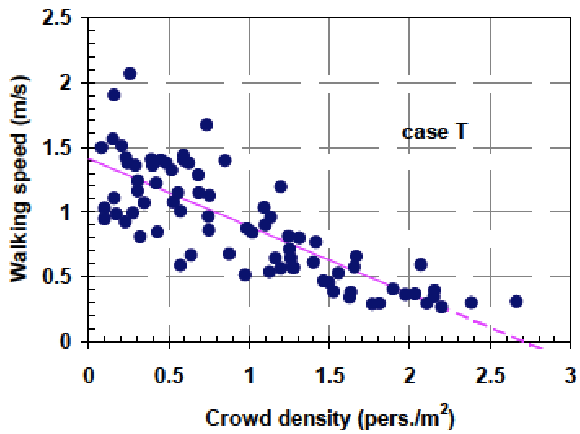


FIGURE 2.6: The relationship between walking speed and crow density[10]

2.2.2 The Characteristics of Underground Tunnel

Tunnel types, geometric features and the locations of ventilation systems, and the guiding sign play the important roles in deciding the evacuation time. They will affect people's decision and vision to evacuate.

2.2.21 Types of Tunnel

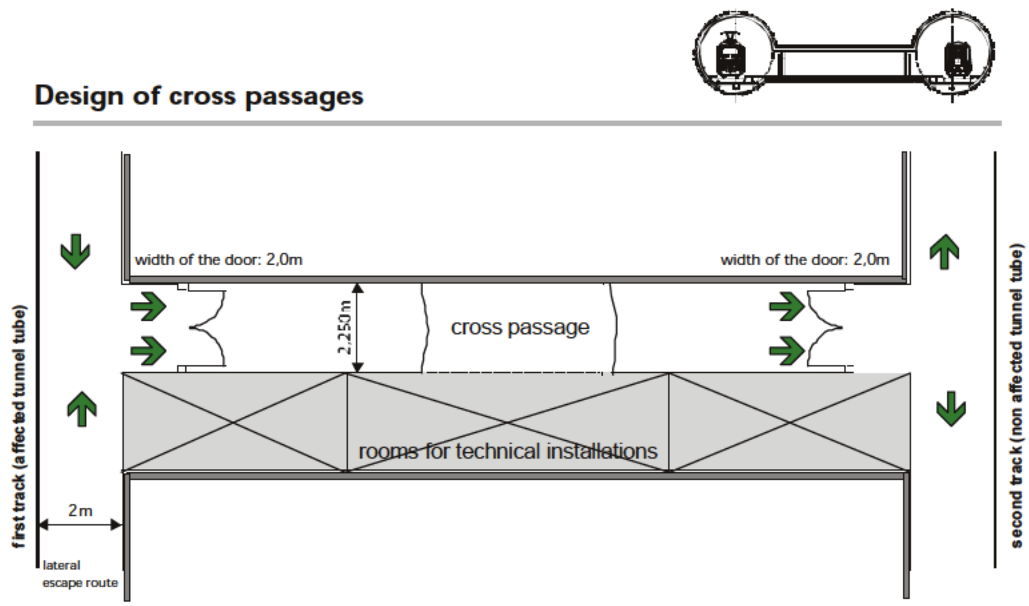
Different types of tunnel also affect the outcome of a fire emergency. Kohl et al. [11] mentioned that there were two different tunnels: a twin-bore tunnel with cross-passages and a twin-track tunnel with emergency exits (See Figure 2.7). The authors used these two types of tunnel to compare evacuation time for the given scenarios. Caliendo et al. [52] explore that the effects of fire bi-directional traffic and one-way tunnels, and find that it could be worse in road tunnels affected by bi-directional traffic. The reason is that the fire in bi-directional tunnels may form a queue in each travelling direction, which might prohibit the emergency vehicles from entering the tunnel to rescue people.

2.2.22 The Geometric Characteristics

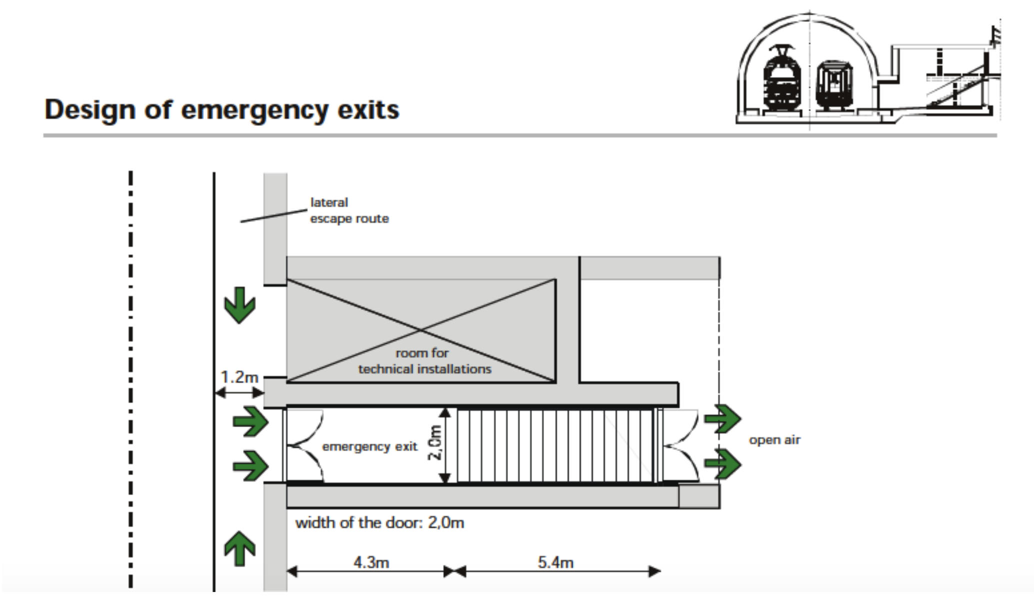
Liu et al. [53] studied that the influence of the walkway width and cross-passageway spacing on the egress time and queuing patterns during the evacuation by using an agent-based continuous crowd simulation model. The authors also pointed out that the distance between cross-passageways was highly related to the optimized evacuation route choice strategy. Haack and Schreyer [47] suggested that the evacuation time is related to the stair capacity for solid stairs in underground stations. Findings of the article show that the evacuation time can be shortened by increasing stair capacities. Roh et al. [54] used fire simulation and evacuation simulation to show that the effect of platform screen door (PSD) and ventilation on passenger's safety in case of a subway train fire. The result showed that passengers in platform with PSD and ventilation system tend to use less time to evacuate than passengers in case without PSD and ventilation system.

2.2.23 Tunnel Ventilation Systems

According to the book called operational guidance: incidents in tunnels and underground structures [55], tunnel ventilation systems can be categorized into four main types, including: longitudinal ventilation, semi-transverse ventilation, full-transverse ventilation and single-point extraction. These different types of ventilation systems



(a) Twin-Bore Tunnel – design of tunnel system and emergency exits



(b) Twin-Track Tunnel - design of tunnel system and cross-passages

FIGURE 2.7: Two Types of Tunnel [11]

control air flow and affect the efficiency of evacuation procedures. Colella et al. [56] also stated that the effect of different ventilation systems mainly depended on their characteristics. Transverse and longitudinal ventilation systems were the most two commonly adopted types. The authors introduced three novel modelling approach for ventilation flow in tunnels: mono-dimensional model, CFD model and multi-scale model. In the work of Meng et al. [57], numerical simulation was applied to investigate the optimization of ventilation mode for smoke control of train fires at the subway station with full-seal PSD or half-height safety door.

2.2.24 Effect of Ticket Gate

When evacuation happens, the ticket gate will be a very critical point influencing efficiency of evacuation. When pedestrian density is small, the efficiency of evacuation in the station will not change too much no matter which type of gate used. While the pedestrian's density is high, the point of ticket gate will be very crowded, which might cause serious congestion. The efficiency of evacuation can be affected by three main factors: the direction of ticket gates (one-way or two-way), the width and the location of the ticket gate. According to Station Planning Standards and Guidelines [58], the combination of one-way and reversible gates should be included in the gate line. The gate should be changed to bi-direction gate at the peak hour. Li et al. [59] presented that the width of the gate usually tends to be small which is generally 0.55 m.

2.2.25 Evacuation Related Facility and Guiding Sign

Evacuation related facility is an essential part of underground transportation infrastructure. Cheng and Yang [3] mention evacuation passages include passage, stair, escalator, turnstile and exit. When an emergency happens, a great number of passengers will run to the evacuation passage, which can cause congestion and queue. The size and capacity of this passage are really important to efficiency of evacuation and people's safety. In case of emergency, Zhao and Tang [12] also point out the several facilities and corresponding functions in the underground including entrance and exit, staircases and elevators, alarm facilities, communication facilities, fire facilities routes and emergency ventilation facilities.

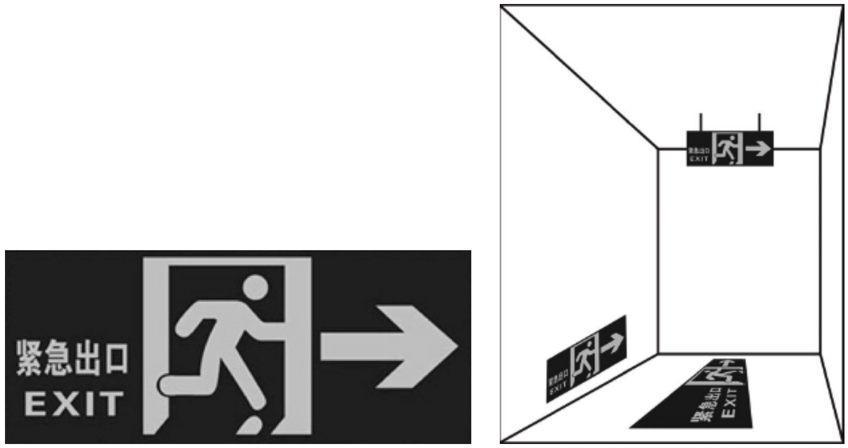
Under an emergency situation, the lack of lighting and evacuation guidance sign, people may feel difficult to identify the right direction to move. Therefore, appropriate guiding sign can improve the efficiency of evacuation from the underground tunnel. Cheng and Yang [3] conduct research and experiments to test whether the guiding information is suitable for the emergency. They make the conclusion that useful guiding information for evacuees is beneficial for improving the evacuation capacity of the subway station and helping evacuate to a safe place as quickly as possible. Zhao and Tang [12] find different designs in metro system and compare their advantages and disadvantages in dealing with the emergency situation. For example, in large-scale subway station entrances and exits, "Emergency Exit "signs are positioned on the wall and ground (See Figure 2.8). In addition, simple and accurate information will greatly decrease response time of evacuees [60].

2.2.3 Smoke, Fire and Train Stopping Location

When fire emergency has already happened, the factors including smoke, fire and train will dramatically affect the outcome.

2.2.31 Smoke Factor

Jin [13] conducts an experiment in a 20-meter long corridor filled with smoke, and concludes that smoke density affects the walking speed apparently. Figure 2.9 shows that the walking speed in both situations reduces gradually with the smoke



(a) Emergency exits

(b) The position of emergency sign

FIGURE 2.8: Emergency Exit Sign and Position [12]

density increasing. For a large-scale subway fire, smoke is an important factor that influences the evacuation process. Generally, the smoke consists of carbon monoxide, carbon dioxide, chlorine and hydrogen cyanide. Several factors affect the severity of smoke including smoke flow, smoke density, temperature and concentrate of CO and CO^2. Zhou et al. [61] apply a dynamic grid technique to research the law of smoke flow diffusion during a fire in the tunnel. The authors simulate the orientation of smoke diffusion when the train decelerates. Tsukahara et al. [43] investigated the influence of smoke, temperature and toxic gases by fire dynamics simulator model when a fire source in the third basement floor in a given subway station. Then they proposed a new subway station with fourth basement floor and downward evacuation routes to substitute the original one. Finally, they concluded that downward evacuation could be more effective than upward evacuation for a large-scale subway fire. Kashef et al. [62] also did certain research on smoke effect that experimental reduced-scale tests were carried out to investigate the smoke temperature distributions under the tunnel ceiling and diffusion distance. In Ronchi et al. [14]'s research, it proved that evacuation time increased with higher smoke density and lower initial walking speeds. (See Figure 2.10)

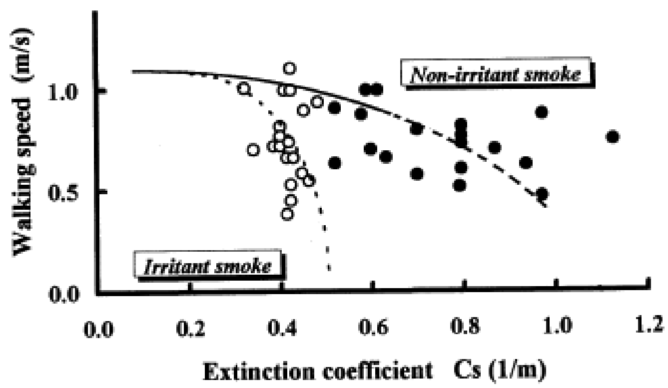


FIGURE 2.9: Walking Speed in Fire Smoke [13]

2.2.32 The Location of Fire

Kohl et al. [11] studied two scenarios with and without smoke. The authors measured the evacuation time of each scenario when the fire happened in different locations inside the train: fire at the rear end of train, in the middle section of train and at the front of the train. The results showed that the evacuation time is substantially influenced by the position of the fire inside the train. Tsai et al. [63]discussed the influence of the distance of fire from the tunnel exits. The authors found out that the distance of fire affected the velocity of critical ventilation. By using small scale experiments, they located fire at 0.5 m, 1.0 m and 1.5 m from the tunnel exit. Finally, the authors proved that the critical ventilation velocity decreased when the fire source was near the exit. Jain et al. [64] presented that the location of fire source inside compartment was an important factor. It was observed that the fire source should not be placed in the center of the compartment and it should be positioned at or near

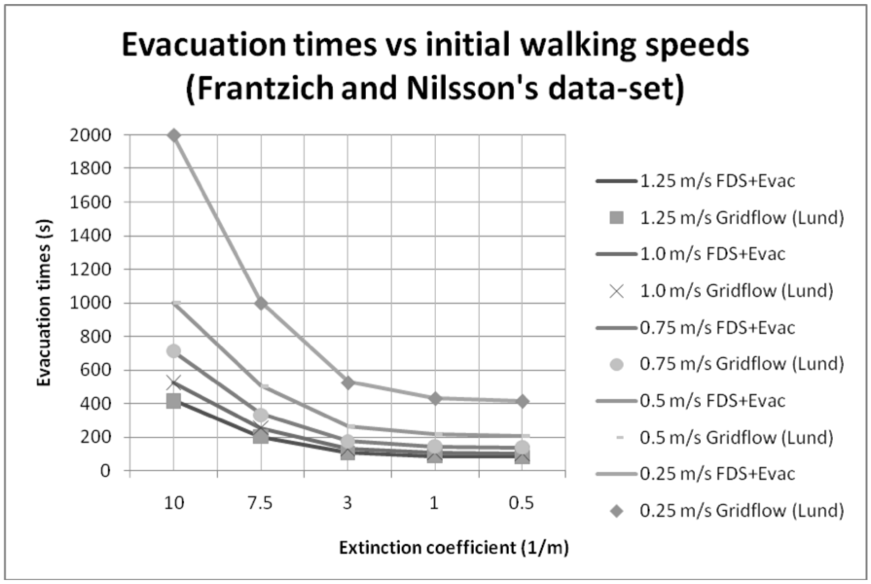


FIGURE 2.10: The trend of the evacuation times vs walking speed and smoke density applied in Frantzich/Nilsson (Lund)'s dataset [14]

vents. Caliendo et al. [52] also mentioned that the severity of a tunnel fire depended on the position where the fire took place in the longitudinal direction.

2.2.33 Train Stopping Location

Wang and Lo [65]discussed about the influence of train stopping location on evacuation. The authors used several performance indicators to measure the outcome, including total clearance time, average egress time, average travel time as well as the average delay time. They found out that the total clearance time was minimal if the train stopped right between two cross-passageways. Hou et al. [66] studied the relationship between the location of train stopping and the critical velocity in tunnel, and the result was that when train stopped in the upstream of tunnel, the air velocity value through the connected aisle was 0.41m/s. When the train stopped in the downstream of the tunnel, the value of velocity reached 0.3m/s. The velocity in cross-passage reached higher value (0.7m/s) when the location of train was in middle of the tunnel. Kohl et al. [11] also discussed that different positions of the train were related to the cross passages during the fire emergency. By using BuildingEXODUS, they simulated in the built environment and counted the evacuation time. (See Figure 2.11)

Based on the discussion above, the critical factors are summarized into the following Figure 2.12.

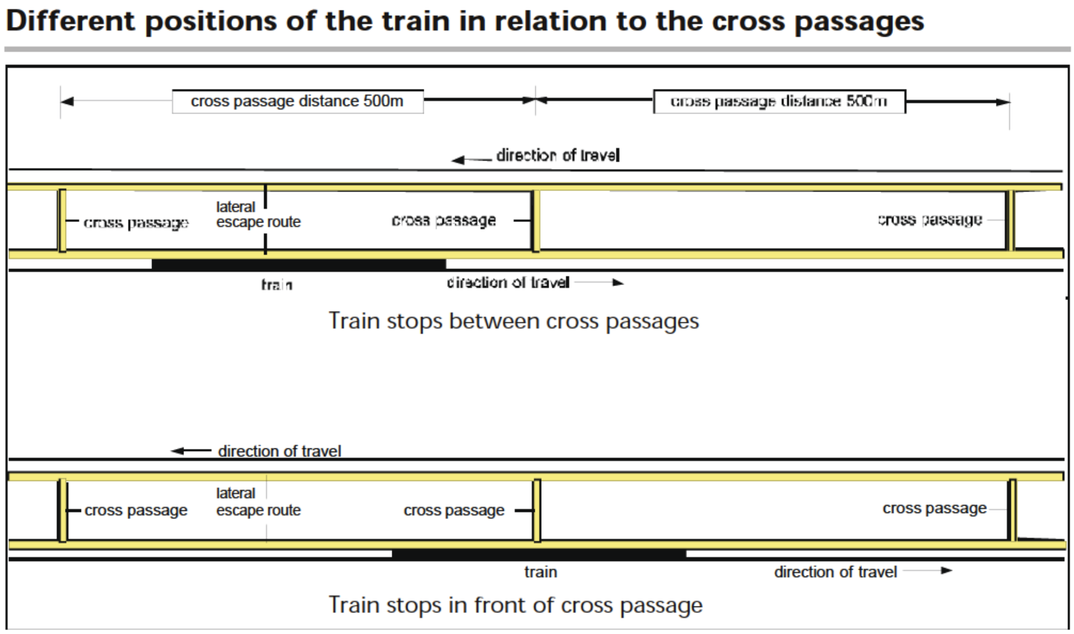
2.3. Pedestrian Modelling

To comprehensively understand human behaviour during the fire emergency in underground transportation systems, pedestrians modellings have been developed over the past decades.

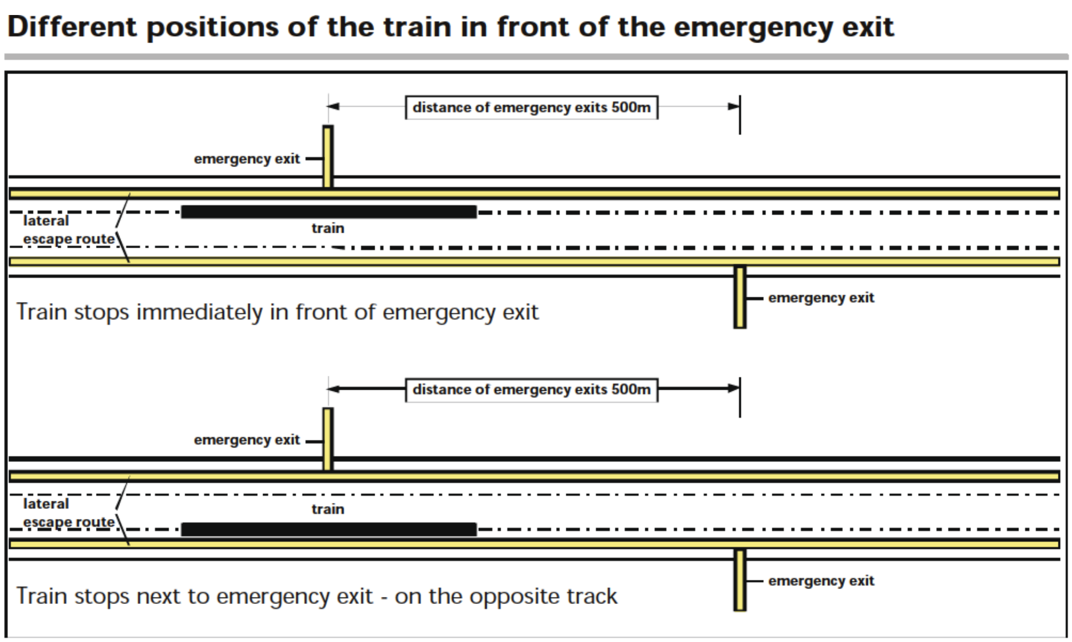
Duives et al. [67] divided pedestrian modeling into eight categories: Celluar Automata Models [15, 67, 68], Social Force Models [6, 69, 70], Activity choice Model [71, 72], Velocity based Models [73, 74], Continuum Models [75, 76], Hybrid Models [77, 78], Behavioral Models [79] and Network Models [80, 81]. Harney [82] also mentioned Celluar autimata Models and social force models. Meanwhile, he reviewed agent-based model and visibility graph Analysis as well. Cheng [83] introduced three microscopic pedestrian modelling: social force model, cellular automata model and agent-based model. Therefore, pedestrian modelling basically can be summarized into following main categories: Social Force Models and Celluar Automata models.

2.3.1 Social Force Model

Social Force Model was first mentioned by Henderson [42]when he built his fluid crowd modeling method. Helbing and Molnar [6, 69] provided this pedestrian modelling to examine pedestrian movements in either positive or negative social fields [82].



(a) Position of Train in the Twin Bore Tunnel



(b) Position of Train in the Twin Track Tunnel

FIGURE 2.11: Position of Two Types of Tunnel [11]

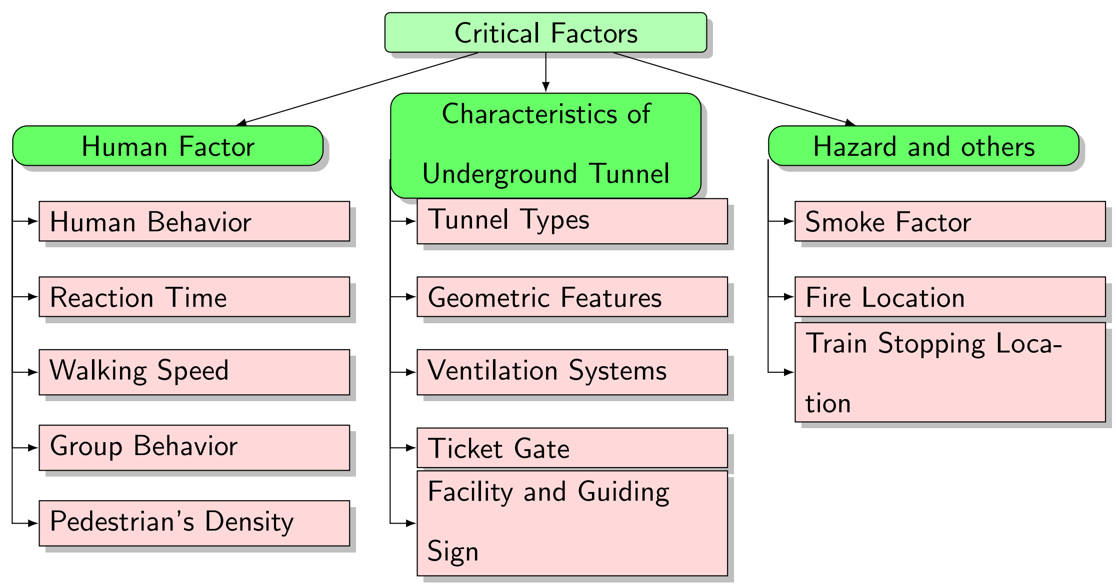


FIGURE 2.12: Summary of Critical Factors affect Evacuation Time

Social force models are applied to research pedestrians movements at a microscopic level [67]. The basic equation [6] of crowd dynamics of pedestrians is based on a generalized force model. Formula is as follows:

$$m_i \frac{dv_i}{dt} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{\tau} + \sum_{j \neq i} f_{ij} + \sum_W f_{iW}$$

(2.2)

Where:

m_i : N Pedestrian i with mass m_i

v_i^0 : desired speed v_i^0 in a certain direction e_i^0

v_i : actual velocity v_i with a certain characteristic time τ_i

$r_i(t)$: change of position $\frac{dv_i}{dt}$

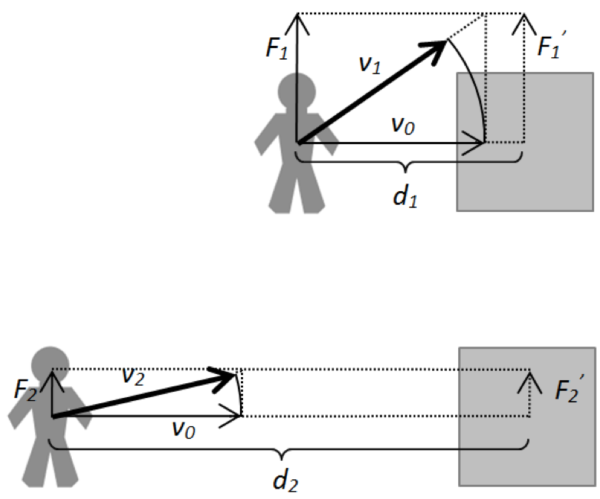
The characteristics of social force model can be summarized as: (1) respect for individuals' space; (2) psychological tendency to stay away from each other; (3) avoid getting close to the obstacles or wall [15] (See Figure 2.13).

2.3.2 Celluar Automata Model

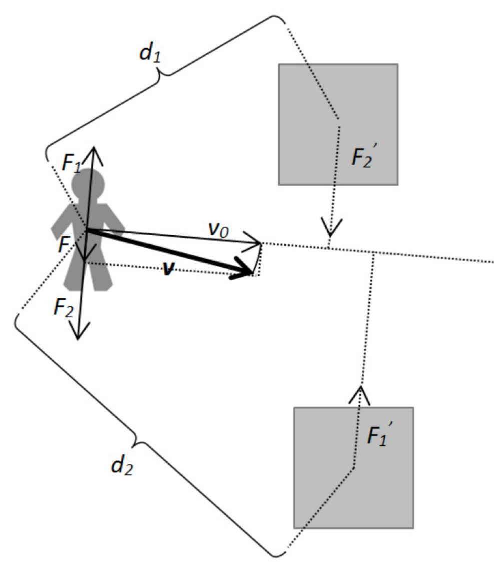
Cellular automata model has been applied for pedestrian simulation provided by Blue and Adler [68]. This model uses grids of cells to stand for pedestrian. The state of each cell is either occupied or unoccupied by a pedestrian [15]. When the pedestrian moves from one position to another, the decision of movement is based on the status of neighboring cells [67]. That means pedestrian will change directions when the forward position was occupied.

2.4. Summary

According to above mentioned literature review, all these accidents can rarely be explained by only one key factor. However, all these types of accidents are explained by a series of critical factors which cause the severe consequence together. In order to minimize the damage and loss in the emergency, interdisciplinary framework approach should be considered in future work and study.



(a) Obstacle repulsive forces: the closer pedestrian is to the obstacle, the bigger the repulsive force



(b) composition of two repulsive forces from two obstacles

FIGURE 2.13: Social force model: One attractive and two repulsive forces [15]

3. METHODOLOGY: AN INTERDISCIPLINARY AGENT-BASED MODELING FRAMEWORK

3.1. Interdisciplinary Framework

An interdisciplinary research essentially consists of two or more disciplines, which can make a separate contribution to the overall study [84]. The National Science Foundation (NSF) defined this term that

> Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice [85].

As Preston and Kolokitha [86] mention that interdisciplinary has become a popular word in research terms. There are certain connections between disciplines. Kempf et al. [87] also discussed that the interdisciplinary approach for their project was the engagement of different research ranging from basic material physics to technological development of individual and group sociology. Consequently, interdisciplinary framework approach is to consider multiple factors when facing a problem. For instance, under this circumstance, the interdisciplinary framework for the factor affect evacuation process consists of three components: psychology area, engineering area and hazard area (See Figure 3.1). The overlapped parts are what this research focused on. In most situation, to investigate the reason for underground accident, people just consider sole factor while most problem cannot just be explained by one reason. It should integrate the different disciplines to foster interdisciplinary research on multiple factors. In the following thesis, interdisciplinary framework will be explained in details.

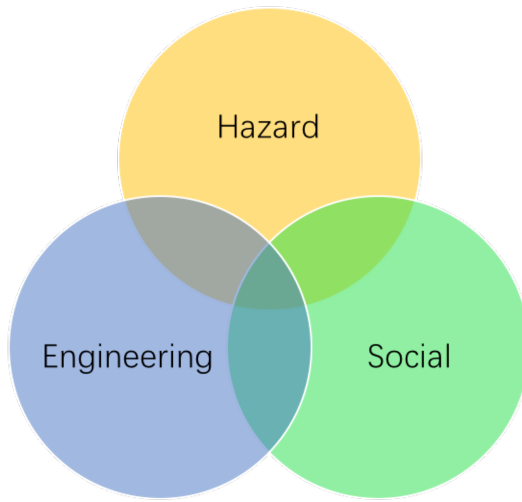


FIGURE 3.1: Interdisciplinary Framework (The area overlapped is what we addressed)

In this thesis, the interdisciplinary framework integrates the following three disciplines: hazard science, engineering, and social science. Figure 3.2 shows the different factors considered in this interdisciplinary framework for underground emergency evacuation.

3.2. Agent-based Modeling and Simulation

3.2.1 What is Agent-based Model and Simulation?

Agent-based model simulation (ABMS) is a relatively new method which can model systems included individual, autonomous, interacting agents [16]. In Bandini et al. [88]'s research, a model can be an abstract and simplified representation of a given reality or an already existing or something just planned. Agent based model

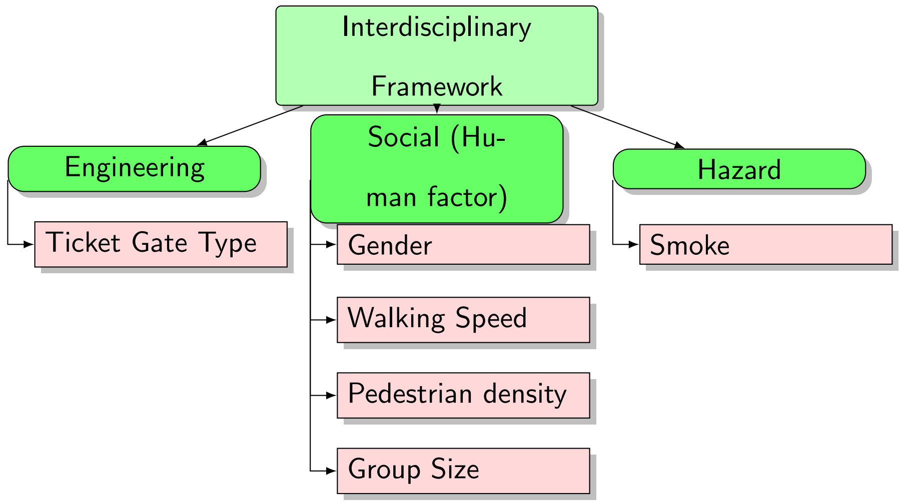


FIGURE 3.2: Factors in Multidiscipline Framework in This Underground Emergency Evacuation

simulation can be characterized by agent-agent interaction and agent-environment interaction. Cheng et al. [83] mentioned that agents followed several rules of behavior in agent-based models. Thus they could appropriately execute various behaviours in the simulation system.

3.2.2 Fundamental Feature of ABMS

According to the work of Wimsatt [89], the characteristics of AMBS can be divided in six components: 1) Agent based modeling have experimental and mathematical style of thinking; 2) ABMS consists of Agents which can represent the individuals in the real world; 3) Agents can interacted with each other and agents can interact with environment as well; 4) Compared to the assumptions of other modeling's, ABM forces us to make more explicit and specific assumptions; 5) ABMS provides more mathematical, theoretical and logical way to explain and predict the outcome; 6) ABMS can explain and discover emergent behavior.

3.2.3 Application of ABMS

Agent-based modeling simulation can be applied in different and large range of research areas, such as business and organization, economics, infrastructure, crowds, society, military and biology etc. In the future, ABMS will be applied in more research fields. More details will be presented in Figure 3.3.

Business and Organizations

- Manufacturing Operations
- Supply chains
- Consumer markets
- Insurance industry

Economics

- Artificial financial markets
- Trade networks

Infrastructure

- Transportation/traffic
- Electric power markets
- Hydrogen infrastructure

Crowds

- Pedestrian movement
- Evacuation modeling

Society and Culture

- Ancient civilizations
- Civil disobedience
- Social determinants of terrorism
- Organizational networks

Military

- Command and control
- Force-on-force

Biology

- Population dynamics
- Ecological networks
- Animal group behavior
- Cell behavior and sub cellular processes

FIGURE 3.3: Agent-based Model Application Area [16]

3.3. Introduction to AnyLogic

In this study, AnyLogic is adopted to simulate the underground emergency evacuation in response to fire emergency. Anylogic is a professional and powerful agent-based modeling platform in which the pedestrian movement and interactions are based on social force model mentioned in Section 2.3. AnyLogic has been applied in many application areas, such as supply chains, healthcare, marketing, manufacturing, military, business, pedestrian flow and transportation simulation. Compared to other simulation softwares, such as Netologo, Simwalk, Anylogic has its own non-substitutable and powerful functions: (1) it can give people vivid visual impact owing to its sophisticated 3D animation functions; (2) it can create rich user interface for the model, thus users can easily control the experiments and change input data and parameters [90]; (3) Anylogic simulation software is simpler and time-saved. Unlike most simulation softwares, it does not require high-level java skills. In Anylogic, users can just drag the tools from Plattee. For instance, when simulating a pedestrian dynamic model, users can just drag what they need from pedestrian library. There is no need to code something complicated; (4) Anylogic simulation software can provide various solutions to manage, plan and optimize simulation in different scenarios. For example, users can personalize several parameters for the specific simulation model. Hu [91] established a pedestrian simulation model by using AnyLogic, and puts several basic parameters in this model, including pedestrian walk speed, size and frequency.

Agent based model is a diverse and complex model, which is not a simple drag-and-drop operation. For agent-based model, there is no standard language to express properly. Instead of using the traditional method, it can be expressed by flowchart, graphics and other ways. It is very difficult to explain the inside dynamic. But in AnyLogic, it supports state charts and action charts, object-oriented and Java.

Additionally, it has the ability to use system dynamics and process flowcharts to allow the building of industrial strength agent-based models [92].

3.4. AnyLogic: Pedestrian Library for Evacuation Modeling

In this thesis, we use the pedestrian library to simulate pedestrian behavior and action during underground emergency evacuation. In Fang et al. [93], for this agent-based model, pedestrian evacuation process consists of perception, decision-making and action perception. In the following study, simulation will focus on the process of pedestrian's action perception. To simulate these specific actions, pedestrian library in AnyLogic will be widely used.

3.4.1 Basic Process of Evacuation in Pedestrian Library

The pedestrian movement process can be basically divided in two aspects: entering process and exiting process. The basic process of pedestrian movement can be presented in the following flowchart. (See Figure 3.4 and Figure 3.5.)

In Anylogic, this process will be presented by pedestrian library. The pedestrian library includes two aspects: Space markup and Blocks. Space markup contains elements for marking up the environment of the process. It incorporates walls, target line, area, services, attractor, pathway, etc. For example, "Wall"is the space markup which can be applied to define exterior and interior walls in pedestrian simulation models [17]. Blocks is the elements which can be used to draw the flowchart. Blocks includes PedScource, PedSink, PedGoTo, etc. Take this flowchart in Figure3.3 as a simple example. Pedsource means the beginning of the pedestrian flow. In this case, it can be pedestrian flow from subway entrance. PedGOTo is for pedestrian go to a target place. In this model, it can be presented as pedestrian go to a ticket machine.

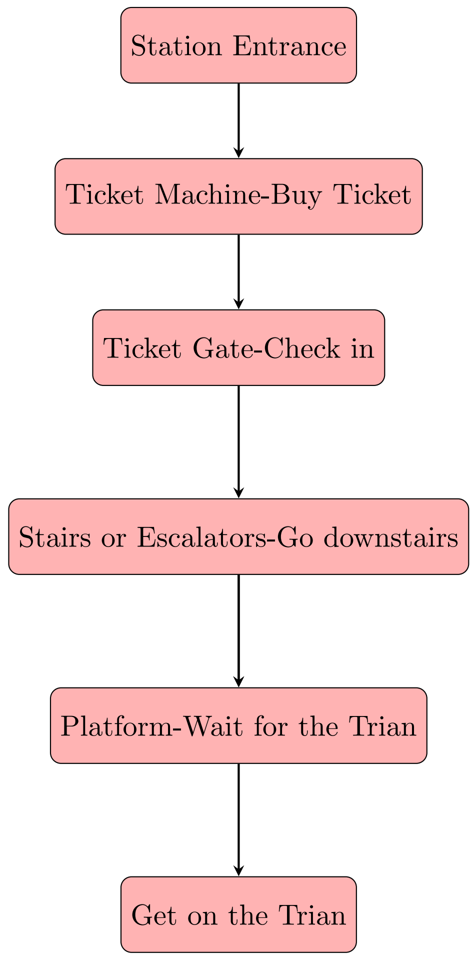


FIGURE 3.4: The Entering Process of Pedestrian Movement

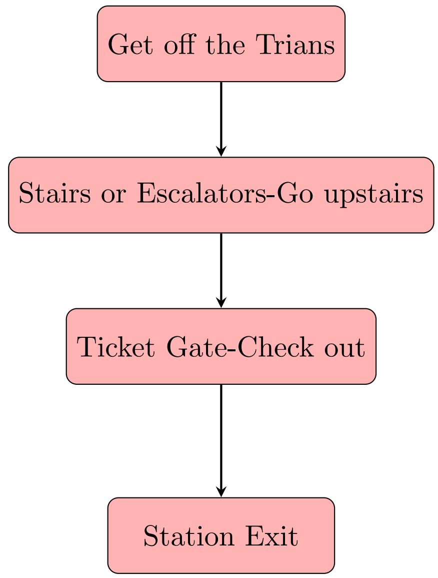


FIGURE 3.5: The Exiting Process of Pedestrian Movement

Pedsink is the end point of the pedestrian flow.

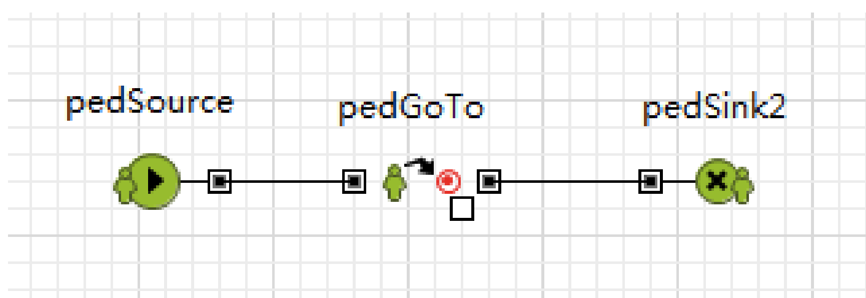


FIGURE 3.6: Simple flowchart in Anylogic

3.4.2 Overview of Subway Stations

This subway station is a regular island platform subway station with three floors, which are ground floor and two underground floors: the first underground floor (B1 floor) and the second underground floor (B2 floor). B1 floor is the station entrance hall floor, and B2 floor is the station platform floor. B1 floor is chosen as the standard simulation environment in this thesis. Figure 3.7 shows the subway station layout of

B1 floor. As the figure shows, B1 floor has four entrances: Entrance A, Entrance B, Entrance C and Entrance D. Four ticket machines are near the entrances. These tickets gates are separate, which consists of two check-in gate and two check-out gates. All these gates are one-way. That means for check-in ticket gates, pedestrian just can check in but cannot check out in this point. Two escalators are on each side and two stairs are in the middle of the floor, which can help pedestrian to go upstairs and downstairs. In the normal situation, passengers can take escalators or go stairs from B1 floor to the second underground floor B2 floor. The area for B1 floor is almost 1500 m^2.

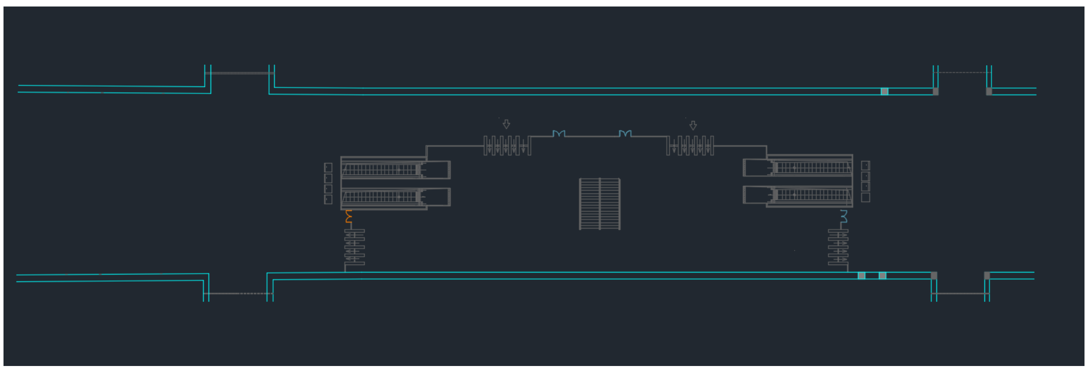


FIGURE 3.7: Subway B1 Floor Layout

3.4.3 Assumptions

- At the beginning of evacuation, pedestrians are randomly distributed on the B2 floor.
- In the simulation process, evacuees tend to choose the nearest gate and entrance to evacuate.
- Once the emergency begins, all escalators will stop and cannot be used during the evacuation process. Stairs on both sides of the floor turn into up-going

operation.

- The evacuation time simulated in this case is just movement time (reaction time is not considered in this situation).

- When considering one parameter, others should be fixed.

3.4.4 Parameter Setup for Evacuation Simulation

Arrival Rate: Pedestrians arrival rate is the rate of pedestrian or groups of pedestrians arrivals in terms of pedestrians (groups) per selected time unit [17]. In this case, arrival rate will set as 1500 persons/hour.

Pedestrian's distribution in B1 floor: Under normal situation, the simulation set 1500 passengers per hour for the inbound number of passengers in each entrance. Under evacuation condition, the total pedestrian is 1500 people in the evacuation. 500 passengers are distributed on the B1 floor. 100 passengers are buying tickets, 150 passengers are about to leave through check-out gate and 250 are going to enter check-in gate. The evacuees who are about to exit from the second underground floor to the first underground floor (B1) are 1000 persons. The simple evacuees distribution is shown in the layout below (See Figure 3.8).

Walking speed: Normal walking speed is average 1.37 m/s. According to Helbing et al. [70], the pedestrian's walking speeds are Gaussian distribution with a mean value of nearly 1.34 m/s and a standard deviation of approximately 0.26 m/s. In this model, pedestrian's walking speed under normal condition will be set as 1.3 m/s. During the evacuation process, although people tend to walk faster than unusual. Fast speed will lead to the congestion and reduce the efficiency of evacuation. According to Knoblauch et al. [94], the walking speed on average is 4 ft/s (1.22m/s) in emergency situations. The walking speed is 1.22 m/s once

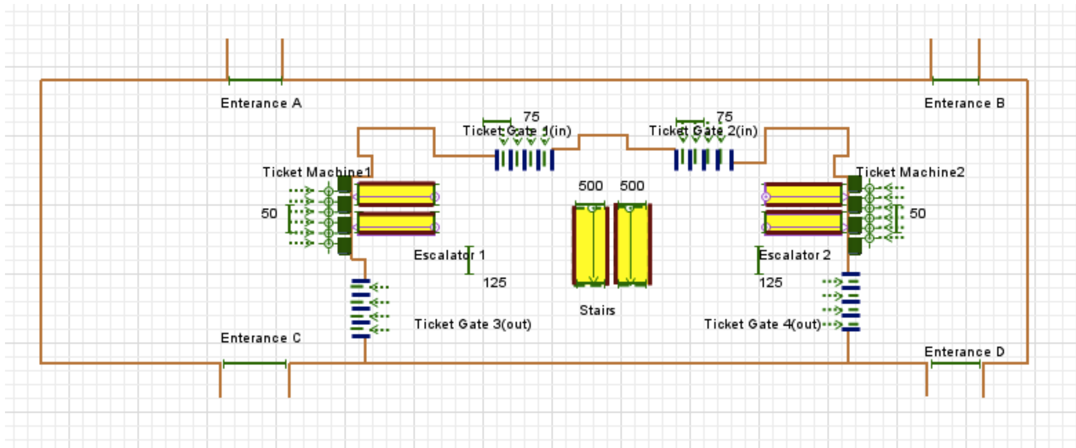


FIGURE 3.8: The evacuees distribution in B1 Floor

evacuation starts. According to Daamen [95], the speed of pedestrians walking on the stairs in the downwards direction is 0.75 m/s and upwards is 0.7 m/s.

Gender: In the simulation, the relationship between gender and walking speed for evacuees is shown in the Table 3.1.

TABLE 3.1: The relationship between gender and walking speed

Gender	Walking speed(m/s)
Female	1.15
Male	1.35

Group size: The researcher makes simulation for group size to observe changes in time with group size changes. Group size is 2, 3 and 4 respectively. To distinguish the influence of different density level, density is divided into two levels: high (1.5 persons/m^2) and low (0.5 persons/m^2).

Pedestrian's density: In the following simulation, pedestrian's densities of 0.2, 0.5, 1.0, 1.5, 2.0, 4.0 persons/m^2 are taken respectively to simulate the pedestrian evacuation. The following equation will be applied to calculate the walking speed individually [10].

$$y = -0.52x + 1.40. \tag{3.1}$$

where:

x : pedestrian density(persons/m^2)

y : walking speed(m/s)

The relationship between pedestrian's density and walking speed for evacuees is shown in the Table 3.2.

TABLE 3.2: The relationship between pedestrian's density and walking speed

Density(person/m2)	Walking speed(low density) (m/s)
0.2	1.296
0.5	1.14
1.0	0.88
1.5	0.62
2.0	0.36

Ticket gate: In this model, ticket gate will be one-way gate and the width of ticket gate is set to be 0.55m.

Smoke effect: From past research, smoke limits the visibility and reduce the speed. Kohl [11] simulated the walking speed with smoke to 50% of the initial speed.

In the work of Galea and Gwynne [96], the average flow rate at the rail exits is estimated to be 9.2 persons/minute in the first experiment, while it is 5.0 persons/minute when the second experiment considers the factor of smoke. Finally, the authors concluded that the situation with smoke doubled the evacuation time. In the following simulation, the fire starts on the B2 floor. Therefore the smoke will spread to the B1 floor from B2 floor. Thus, the arrival rate of B1 floor can be roughly considered as a flow rate from B2 floor. To investigate how smoke affects the evacuation time, arrival rate is set at 1500 persons/hour for the scenario without smoke and 750 persons/hour for the scenario without smoke with smoke, respectively.

3.5. Under Evacuation Situation

When the evacuation happens, all escalators are stopped due to saftey concerns. Thus all passengers use the stairs to escape from the B2 floor to the B1 floor and then they go through two check-out gates to the exits. The total pedestrian is 1500 people in the evacuation. The simple evacuees distribution is shown in the layout. (See Figure 3.8)

3.5.1 Effect of Type of Ticket Gates

Firstly, the simulation will test whether one-way ticket gate is reasonable and how it affects the evacuation process and outcome.

3.5.11 One-way Ticket Gate

In this case, ticket gates for check in and check out are one-direction gates. When the simulation starts, pedestrians escape from the B2 ground to B1 ground by using the stairs then just using ticket gates 3 and 4 to leave. In the following paragraphs, the flowchart of the original layout with one-way ticket gate will be introduced in details.

Evacuees evacuate from the B2 floor: Assume that there are 1000 passengers at the arrival rate as 1500 persons per hour escape from B2 floor by each stair. For the selection of escaping path, 50% passengers choose ticket gate 3 and 4 to go upstairs. After checking out from the ticket gate, they will leave from the entrance. Taking gate 3 as an example. 30% evacuees choose the path to Entrance A and 70% to Entrance C because of the closer distance. The flowchart is shown in Figure 3.9.

Evacuees who are about to check out: Assume that there are 250 pedestrians at the arrival rate of 1000 persons per hour who have already been on the B1 floor and are about to check out. For the escaping path selection, there are 30% evacuees choose the path to Entrance A and 70% to Entrance C because of the closer distance. The flow chart of one stair is shown in Figure 3.10.

Evacuees who are about to buy tickets: Assume that there are 100 pedestrians at the arrival rate of 1000 persons per hour who are in the B1 floor and are about to buy tickets. For the escaping path selection, there are 50% evacuees choose the path to Entrance A and 50% to Entrance C because the distances between each entrance are same. The flow chart of one stair is shown in Figure 3.11.

Evacuees who are about to check in: Assume that there are 150 pedestrians at the arrival rate of 1000 persons per hour who are in the B1 floor and are about to check in. For the escaping path selection, there are 80% evacuees choose the path to Entrance A and 20% to Entrance B because the distances from Entrance

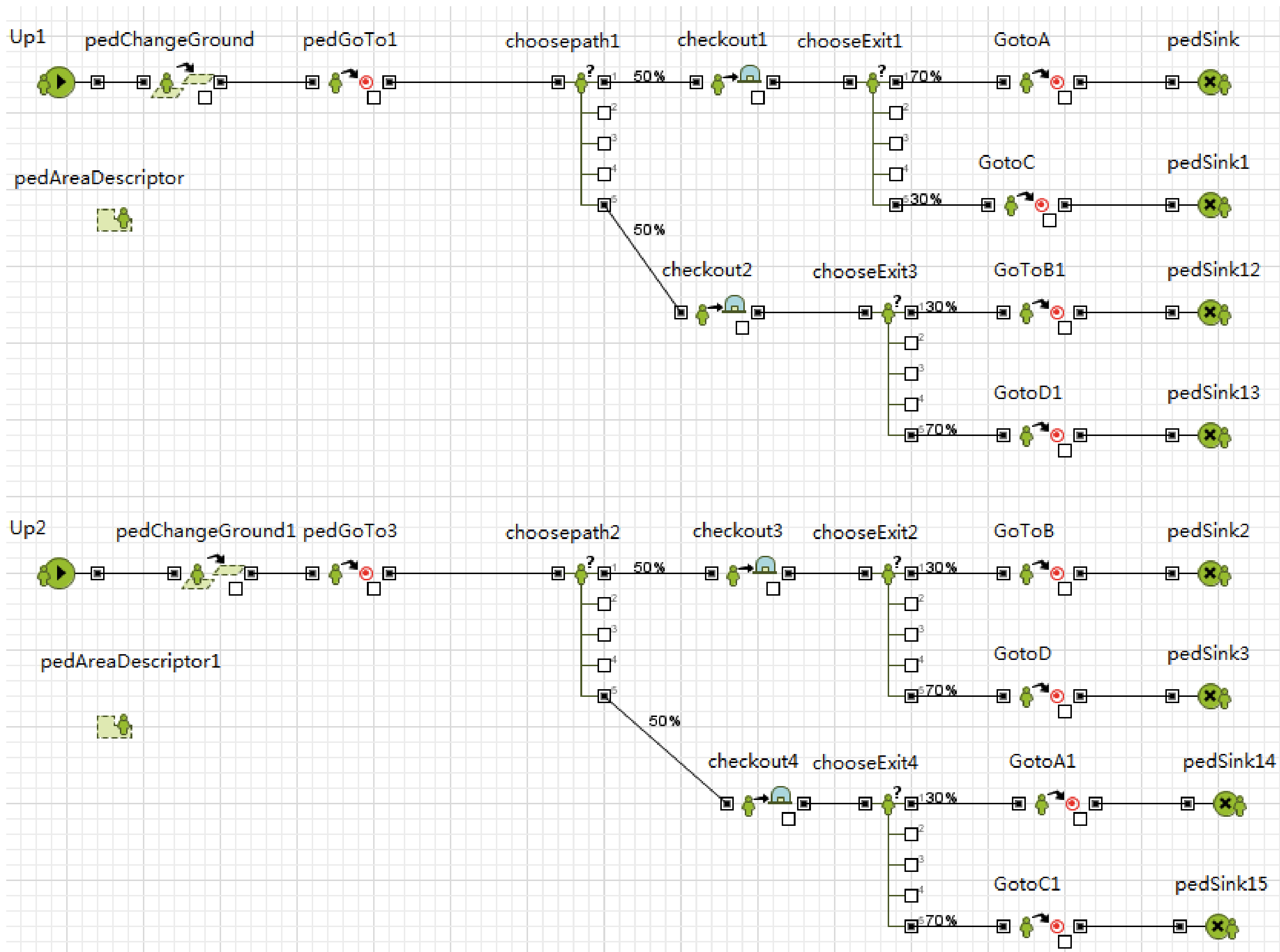


FIGURE 3.9: Evacuees from the B2 floor Flow chart

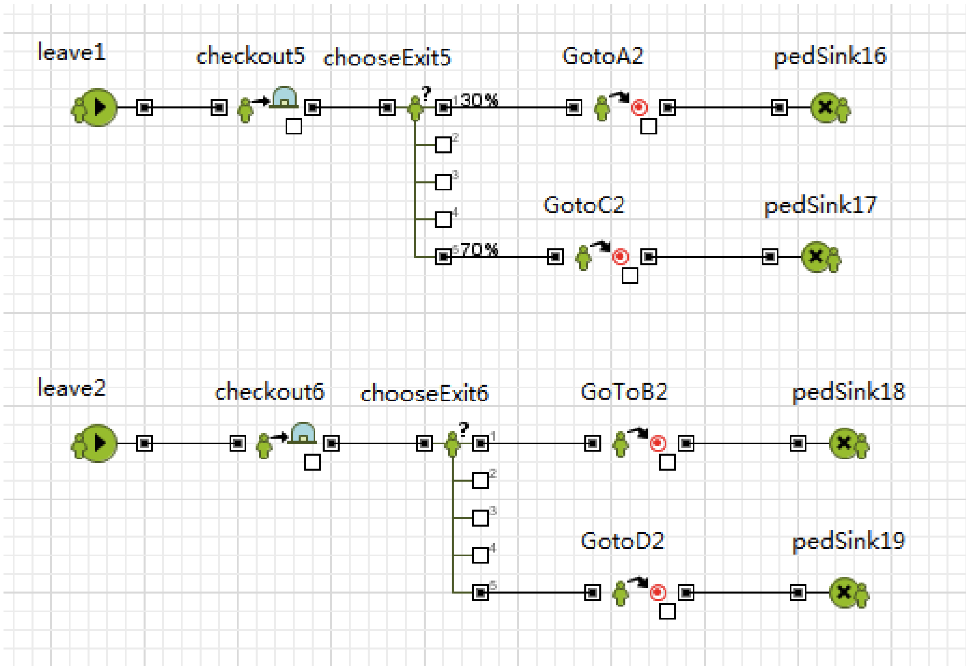


FIGURE 3.10: Evacuees who are about to check out

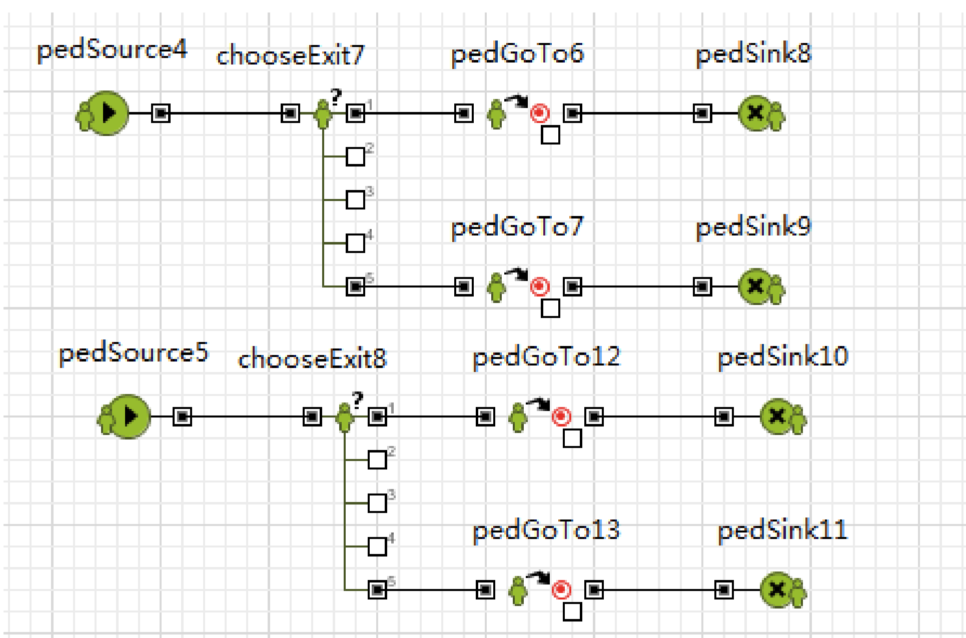


FIGURE 3.11: Evacuees who are about to buy tickets

A is obviously closer. But congestion might cause few people choose Entrance B. The flow chart of one stair is shown in Figure 3.12.

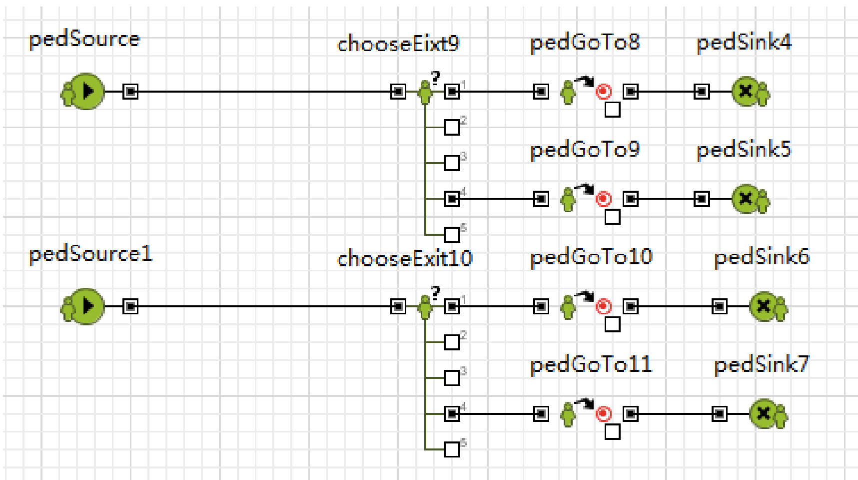


FIGURE 3.12: Evacuees who are about to check in

3.5.12 Bi-direction Ticket Gate

To simulate the effect of ticket gate type, the layout will be changed (See Figure 3.13). Gate 1 and 2 become to bi-direction; that is, they can be applied to check in and check out.

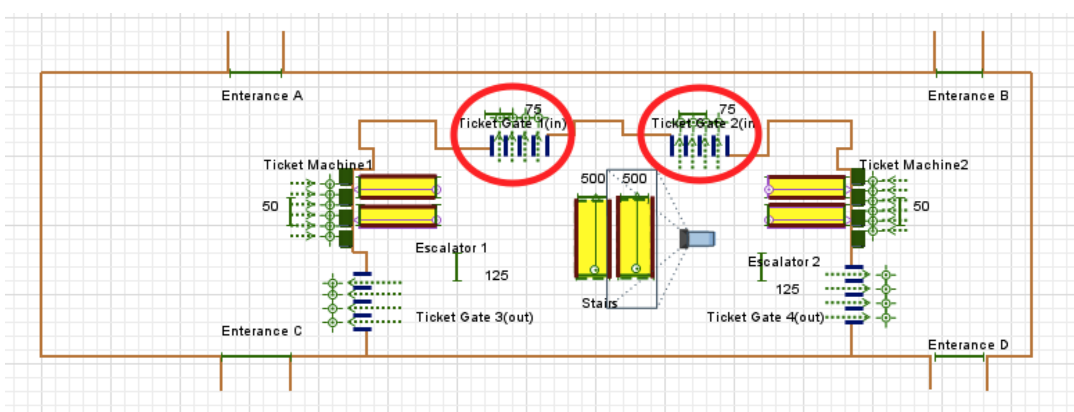


FIGURE 3.13: The changed layout in B1 Floor(bi-direction ticket gate)

Assume that there are 1000 passengers at the arrival rate with 1500 persons per hour who escape from B2 floor by each stair. For the escaping path selection, the situation is very complicated. Because there are four ticket gates during the evacuation process and the movement of evacuees will be influenced by this change. The movement of evacuees evacuate from the B2 floor and people who are about to check out will affect by this change. While the other two types of evacuees have no obvious changes under certain circumstance.

Evacuees evacuate from the B2 floor: For the passenger from the left part, there are 40% passengers who go upstairs choose ticket gate 1 and 2, respectively. The rest of 20% passengers will choose gate 3 and gate 4 (10% for each). After checking out from ticket gate, taking gate 3 as an example, evacuees will leave from appropriate entrance. There are 30% evacuees choosing the path to Entrance A and 70% to Entrance C because Entrance C is relatively closer. For the people who choose gate 1, there are 80% evacuees choose the path to Entrance A and 20% to Entrance B because the distance from Entrance A is obviously closer, but people may choose Entrance B to avoid congestion. The flow chart is shown in Figure 3.14.

Evacuees who are about to check out: Assume that there are 250 pedestrians at the arrival rate of 1000 persons per hour who have already been in the B1 floor and are about to check out. Taking the left part pedestrians as an example. For the escaping path selection, there are 50% evacuees choosing the path to gate 1 and 50% to gate 3 since the distances between each entrance are same. If evacuees choose gate 1, there are 80% evacuees choosing the path to Entrance A and 20% to Entrance B. If they choose gate 3, there are 30% evacuees choosing the path to Entrance A and 70% to Entrance C because Entrance C is relatively

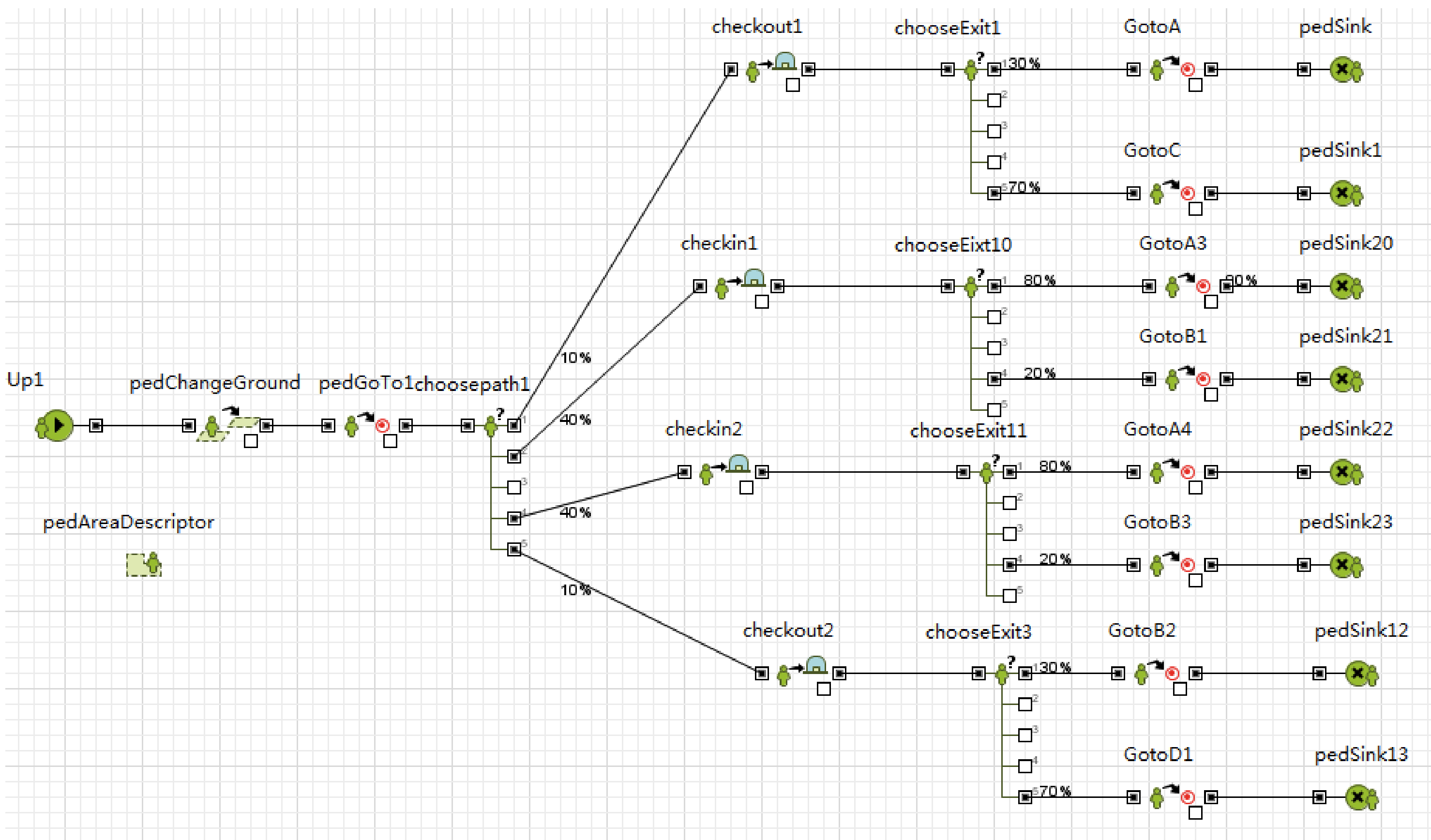


FIGURE 3.14: Evacuees from the B2 floor Flow chart under the condition of bi-direction ticket gate

closer. The flow chart of one stair is shown in Figure 3.15.

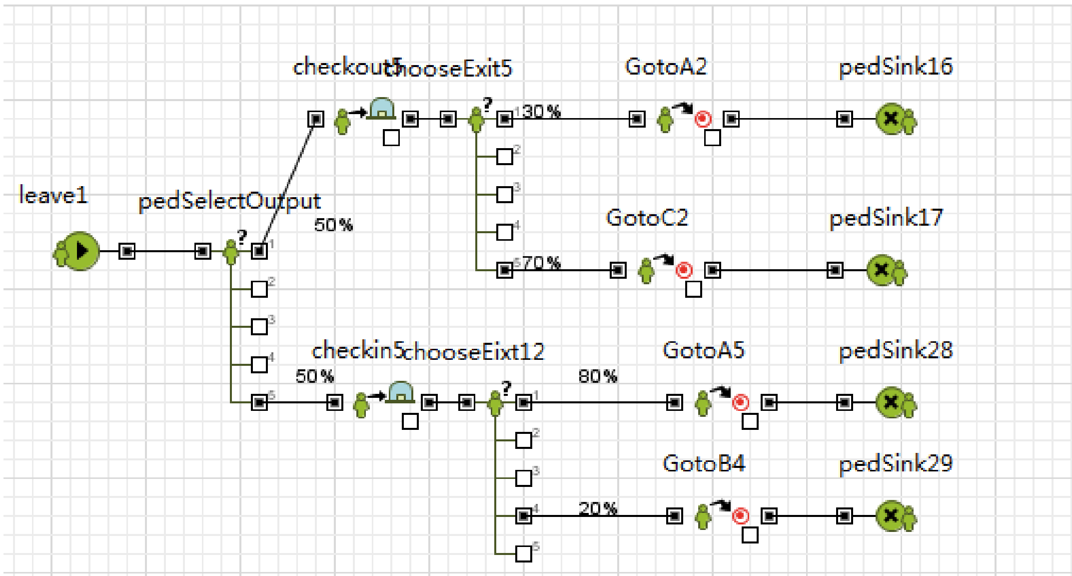


FIGURE 3.15: Evacuees who are about to check out under the condition of bi-direction ticket gate

3.5.2 Effect of Gender

As discussed in section 3.4.4, gender also can affect walking speed and change the evacuation time. To be specific, Table 3.1 shows the gender and walking speed. In this simulation, gender is chosen to be the only variable to control the evacuation outcome (See Figure 3.16).

3.5.3 Effect of Walking Speed

As discussed in section 3.4.4, walking speed can be a very crucial factor which will lead to different evacuation time. In this simulation, five different walking speeds will be chosen to simulate: 0.8m/s, 1.0 m/s, 1.2 m/s, 1.4 m/s, and 1.6 m/s. In this simulation, passengers' walking speed can be a variable to control the evacuation time (See Figure 3.17).

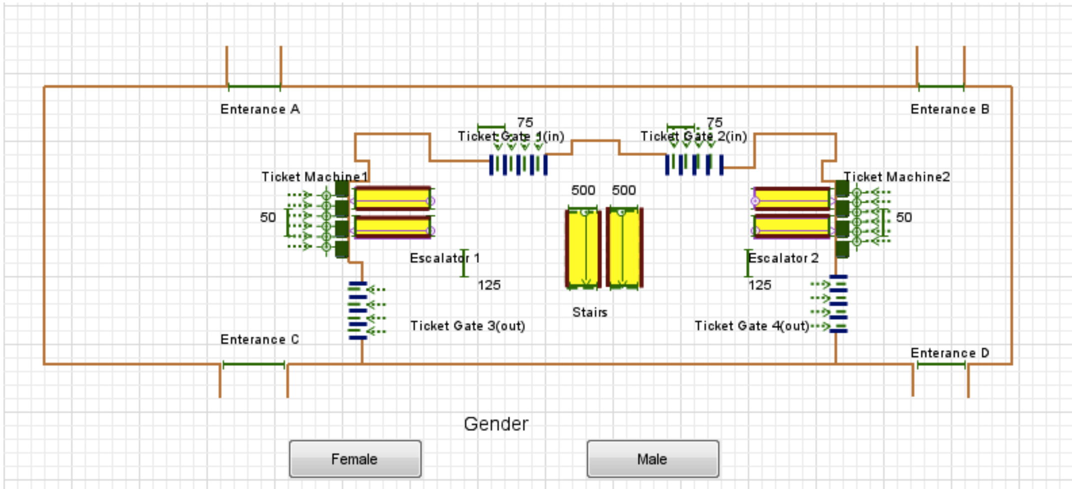


FIGURE 3.16: The Effect of Gender in Anylogic

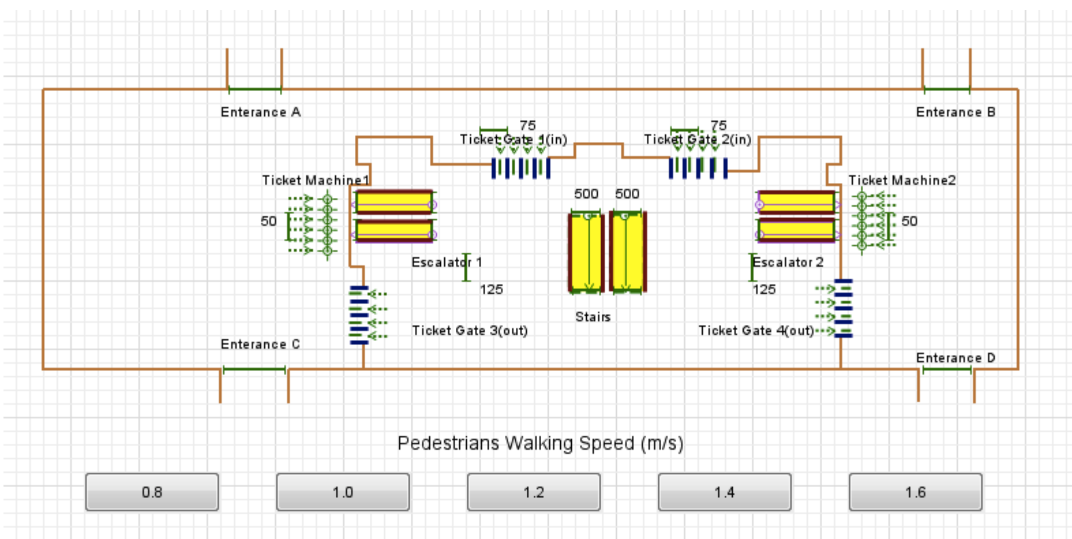


FIGURE 3.17: The Effect of walking speed in Anylogic

3.5.4 Effect of Group Size

According to the discussion above, group size is a key factor which can be a valuable parameter during evacuation. In order to change the group size, Anylogic provides a specific block called PedGroupAssemble. This block could change multiple criteria for groups creation, such as group size, group form and groups arrival rate. Under the circumstance, two areas will be added to apply for group assembly in Figure 3.19. Correspondingly, the flowchart will be changed as well (See Figure 3.18).

In the following simulation, the relationship between group size and evacuation time at different density levels for these evacuees will be presented in Figure 3.19.

3.5.5 Effect of Pedestrian Density

According to the Table 3.2 pedestrian's densities of 0.2, 0.5, 1.0, 1.5, 2.0 persons/m^2 are taken respectively to simulate the pedestrian evacuation. Because the total number of pedestrians during the evacuation will be changed with the different density. The number of pedestrian distribution in each area is presented in Table 3.3.

TABLE 3.3: The distribution of pedestrians in B1 floor

density (persons/m^2)	0.2	0.5	1.0	1.5	2.0
people go upstairs	200	500	1000	1500	2000
people leave	50	125	250	375	500
people check in	30	75	150	225	300
people buy tickets	20	50	100	150	200
Total	300	750	1500	2250	3000

FIGURE 3.18: The flowchart of change group size in Anylogic

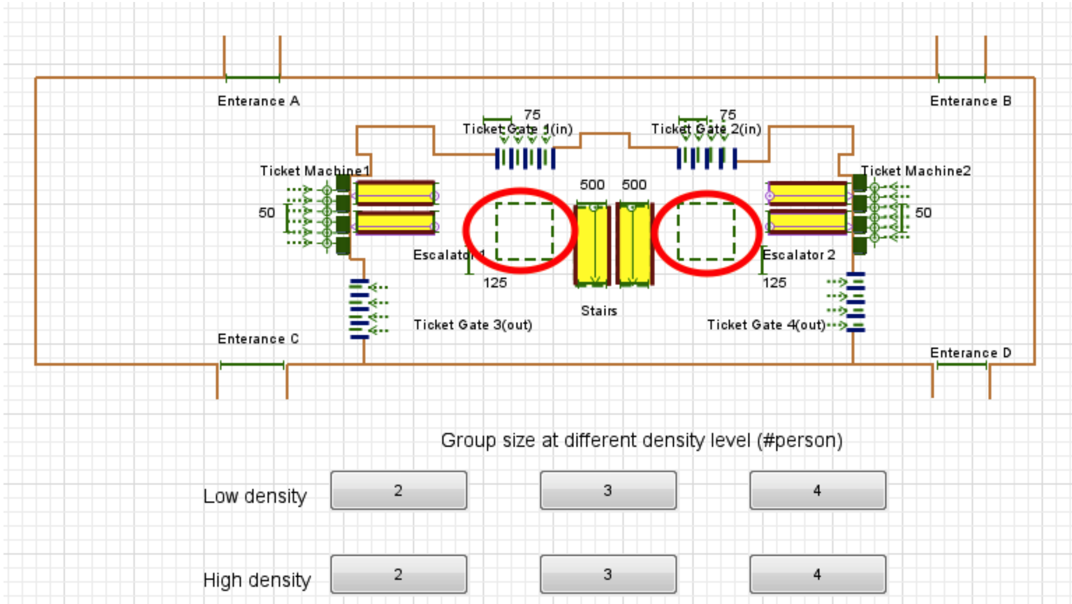


FIGURE 3.19: The Effect of group size in Anylogic

In the following simulation, the relationship between pedestrian's density and evacuation time will be shown in Figure 3.20

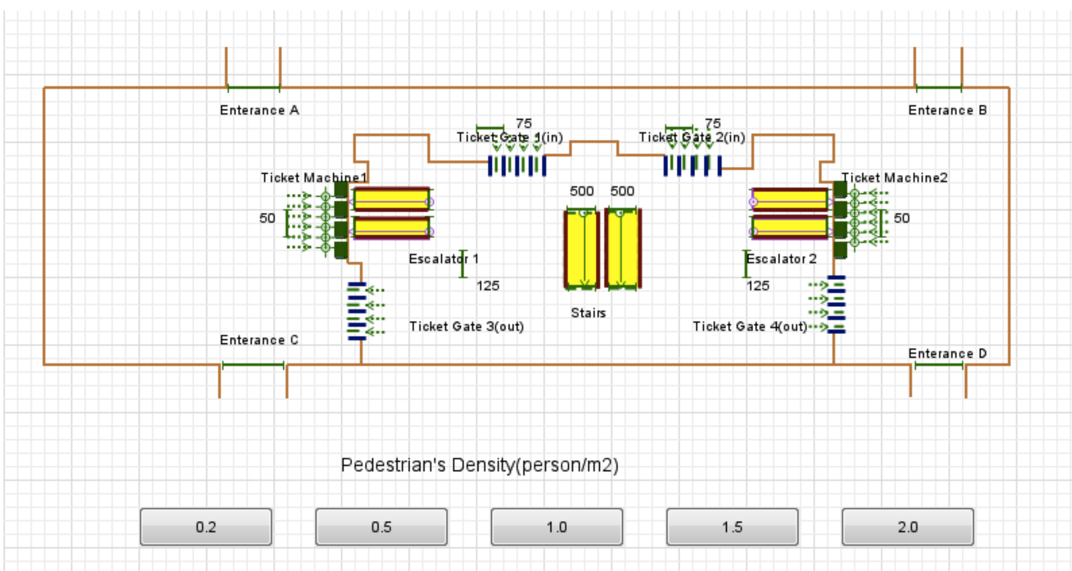


FIGURE 3.20: The Effect of pedestrian's density in Anylogic

3.5.6 Effect of Smoke

According to the discussion from section 3.4, arrival rate on B1 floor equals 750 persons/hour and 1500 persons/hour respectively to simulate the pedestrian evacuation. In this simulation, smoke is chosen to be the only variable to control the evacuation outcome (See Figure 3.21).

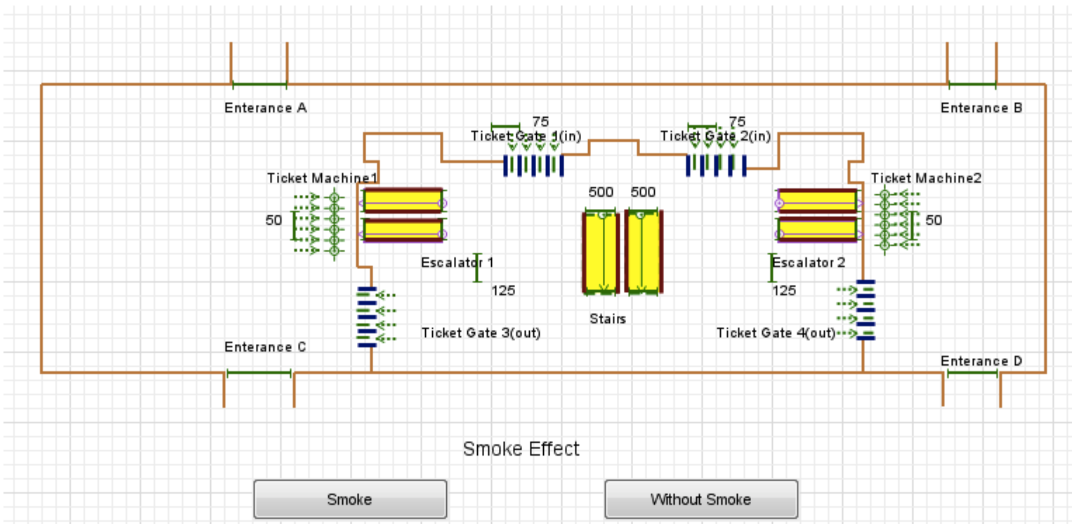


FIGURE 3.21: The Effect of Smoke in Anylogic

3.6. Summary

In this section, a interdisciplinary agent-based modeling framework is proposed to integrate the hazard science, engineering, and social system together. Then, an agent-based underground emergency simulation model is created in AnyLogic. In the next section, the simulation result based on different critical factors involved and their impact on the evacuation time will be deeply discussed and investigated.

4. RESULT AND DISCUSSION

Based on the discussion before, the effect of the parameters involved in the given evacuation scenarios will be thoroughly presented in this section. The total evacuation time equals reaction time plus movement time [10]. Reaction time is highly related to the human factor and very complicated, which will not be considered in this study. However, the movement time is associated with the critical factors, which will be simulated in the following section.

4.1. Effect of Factors

Various factors can affect evacuation outcome and evacuation time, such as the types of ticket gate, walking speed, gender, group size and pedestrian density. The analysis of these factors on evacuation time is studied and simulated in details in the following section.

4.1.1 Effect of Ticket Gate Type

The influence of ticket gate type on evacuation can be implemented in the model by using the "Pedestrian Density Map". It is very clear to show the whole density of pedestrians in the simulated space and display the information which part is more crowded on animation. When pedestrians move in the simulated space, the layout is painted with gradient color, which describes different density of pedestrians [17]. Illustrated in Figure 4.1, from the top to the bottom, the density changes from high to low. For example, red means the highest density which is 1.5 peds/m^2 while blue means lowest density which is 0 peds/m^2.

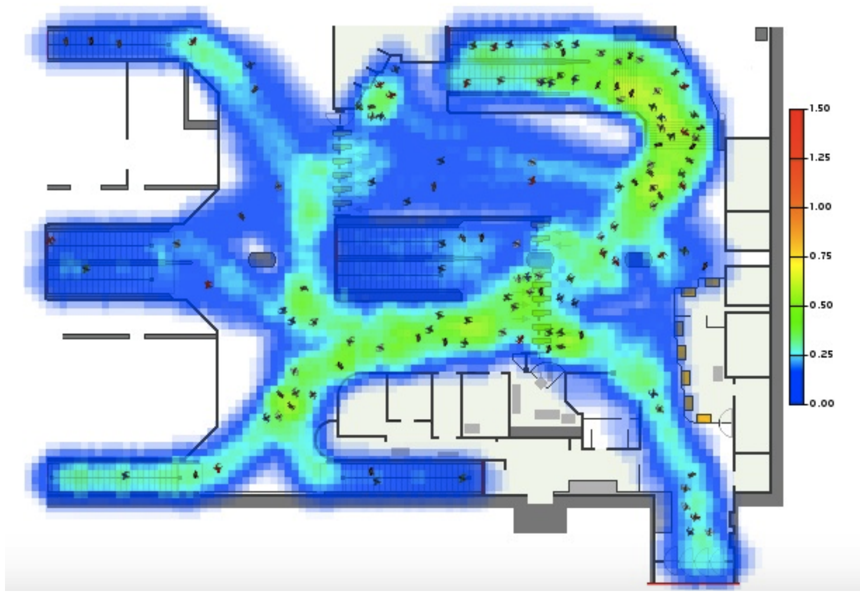


FIGURE 4.1: The example of pedestrian density map for subway entrance hall [17]

The pedestrian density map under the condition of one-way ticket gate is shown in Figure 4.2. According to the pedestrian's flow density mapwe can easily find out that there are high-density evacuees waiting here. The pedestrians' flow causes serious congestion near the stairs and ticket gates 3 and 4.

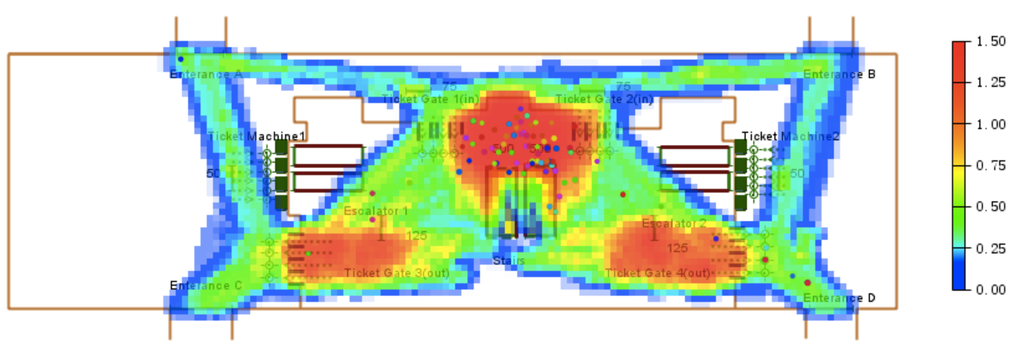


FIGURE 4.2: The pedestrian density map under the condition of one-way ticket gate

To mitigate this congestion, ticket gates 1 and 2 can automatically change to bi-direction gates to evacuate. The pedestrian density map under the condition of bi-direction ticket gates is shown in Figure 4.3. From this figure, the improvement in the changed layout is obvious. Compared with the former design, the area of red is reduced. The serious congestion in check-out part disappeared, so that the changed layout takes effect in this situation.

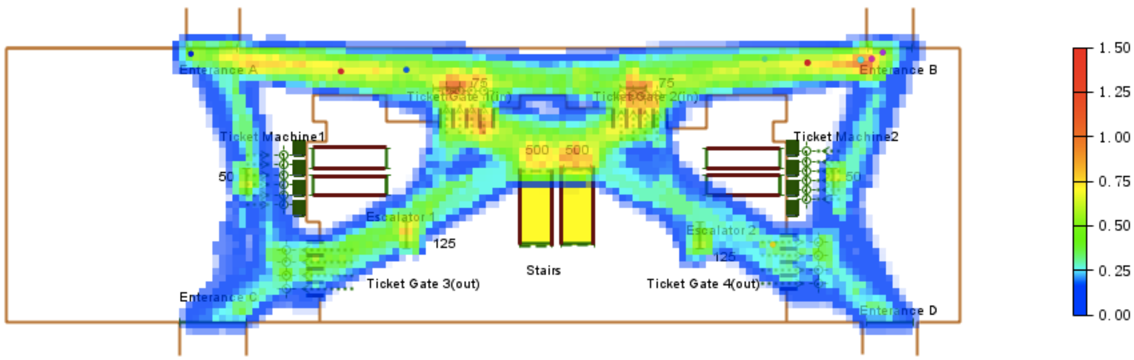


FIGURE 4.3: The pedestrian density map under the condition of bi-direction ticket gate

To test the effectiveness of the changed model, we made experiments to compare evacuation time in these two scenarios. We applied these evacuation times in RStudio, obtaining the plot (See Figure 4.4). As shown in this figure, the type of tickets gates has little influence on pedestrian evacuation time. Table 4.1 presents the mean evacuation time under different ticket gate type. From the table, Standard Deviation (SD) can tell us how much these data vary from it's mean. In this case, those SD are relatively smaller, which means these mean evacuation times are good and can stand for these evacuation times. While, based on pedestrian densities map, the added ticket gates 1 and 2 alleviate the congestion significantly, which make evacuation more orderly and quickly.

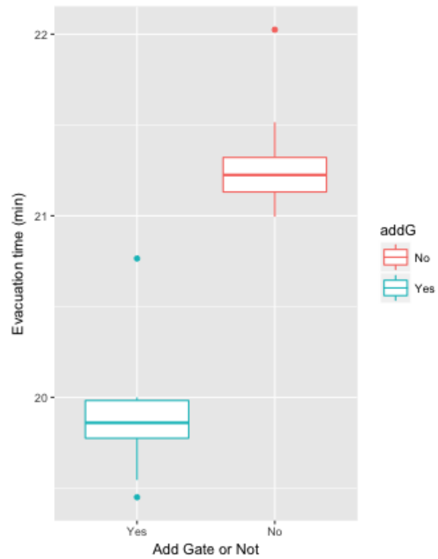


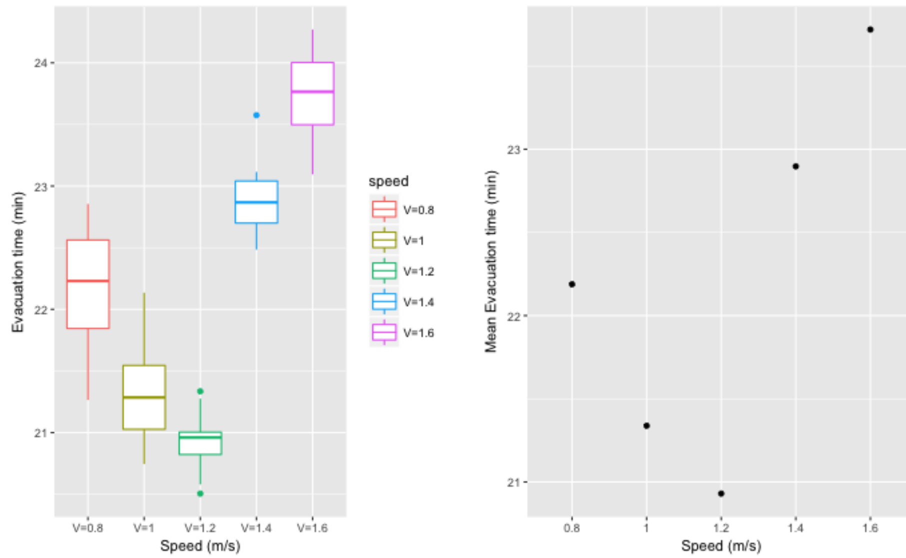
FIGURE 4.4: Impact of Ticket Gate Type on Evacuation time

TABLE 4.1: Impact of Ticket Gate Type on Evacuation time

Add Gate	Mean Evacuation time (min)	SD (min)
Yes	21.3	0.354
No	19.9	0.301

4.1.2 Effect of Walking Speed

As discussed in Section 3.4, walking speed is another critical factor in this study. The speed will be divided into five groups: 0.8 m/s, 1.0 m/s, 1.2 m/s, 1.4 m/s, 1.6 m/s. Figure 4.5(a) shows that walking speed is a key factor to evacuation time. Table 4.2 presents the mean evacuation time under different walking speed. Those SD are relatively smaller, which means these mean evacuation time are good. The relationship between walking speed and mean evacuation time is shown in Figure 4.5(b).



(a) Impact of Walking Speed on Evacuation Time

(b) Impact of Speed on Mean Evacuation time

FIGURE 4.5: Evacuation time and Speed

TABLE 4.2: Impact of Speed on Mean Evacuation Time

Walking speed (m/s)	0.8	1.0	1.2	1.4	1.6
Mean Evacuation time (min)	22.19	21.34	20.93	22.90	23.72
SD(min)	0.525	0.418	0.262	0.317	0.381

According to these statistics and figures, it shows that with the increase of the walking speed, the evacuation time is not decreasing all the time, which means the relationship between two variables is not linear. When speed is low (from 0.8 m/s to 1.0 m/s), the evacuation time decreases with speed increases. In this case, since the walking speed is not too high to gather large number of pedestrians, people can move easily and quickly. However, when walking speed is high enough, large crowds are assembled at the two ticket gates. When the walking speed reaches 1.2 m/s, it comes to the saturated evacuation status. Therefore, if pedestrians walk faster, the evacuation time will not reduce. Because the evacuation area has reached the maximum capacity. It might cause severe congestion when passengers walk relatively faster (over 1.2 m/s). Therefore, it also prove the theory proposed by Helbing et al. [70] that "faster is slower effect ". If people try to move faster, the clogging can cause delays. Under this circumstance, it can cause a slower evacuation.

4.1.3 Effect of Gender

As shown in Figure 4.6, the mean evacuation time for males is 20.4 minutes and females is 22.1 minutes (See Table 4.3). Those SD are relatively smaller, which means these mean evacuation time are good. Males tend to walk faster. Therefore their evacuation time are relatively less than that females.

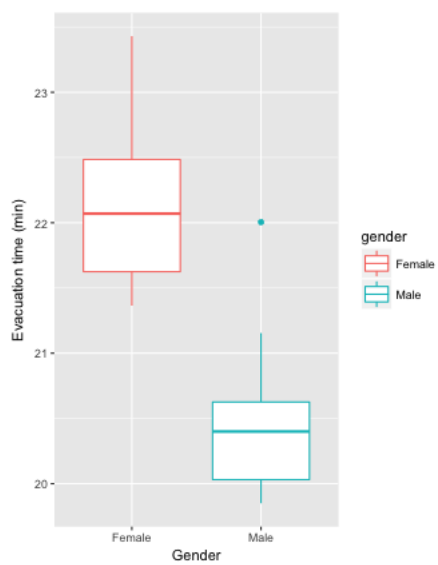


FIGURE 4.6: Impacts of gender on Evacuation Time

TABLE 4.3: Impact of Gender on Mean Evacuation Time

Gender	Mean Evacuation time (min)	SD (min)
Female	22.1	0.637
Male	20.4	0.651

4.1.4 Effect of Group Size

According to the discussion before, group size is an important factor which can be a crucial parameter during evacuation. In the following simulation, the relationship between group size and evacuation time at different density levels presented in Figure 3.19.

As shown in Figure 4.7, group size is positively correlated with the evacuation time. Both pedestrian density and group size affect the evacuation time apparently. When the density level is fixed, the evacuation time increases rapidly as group size grows. Moreover, the group at high density level needs more time to evacuate than the group at the low density level. The relationship between mean evacuation time and group size at different density levels is shown in Table 4.4. Those SD are comparatively smaller, which means these mean evacuation times fit very well.

4.1.5 Effect of Pedestrian's Density

In this situation, densities are set as 0.2, 0.5, 1.0, 1.5, 2.0 persons/m^2. Figure 4.8, it turns out that pedestrian density has a positively correlated with evacuation time. The exact relationship between mean evacuation time and density is shown in below Table 4.5. Those SD are relatively smaller, which means these mean evacuation time are fitting well. From the statistics and figure, as the increase of the pedestrian

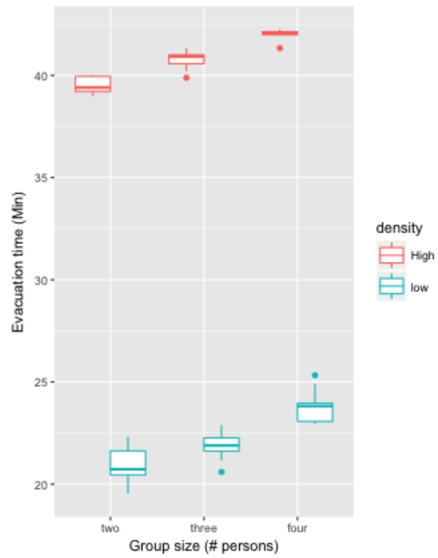


FIGURE 4.7: Impact of Group Size on Evacuation time at different density level

TABLE 4.4: Impact of Group size on average Evacuation time at different density level

Group size (#person)	Evacuation time(low density) (min)	Evacuation time(high density) (min)
2	22.05	39.51
3	22.12	40.77
4	22.38	42.01

density, the evacuation time increases almost linearly. Since once the great number of evacuees gather in one area, the area will be very crowded, which lead to difficulties in evacuation. When the pedestrian density increases gradually, the evacuation time is increasing as well.

Figure 4.8 suggests that there is a linear relationship between the mean evacuation time and pedestrian density. To be specific, the output shows that it fits very

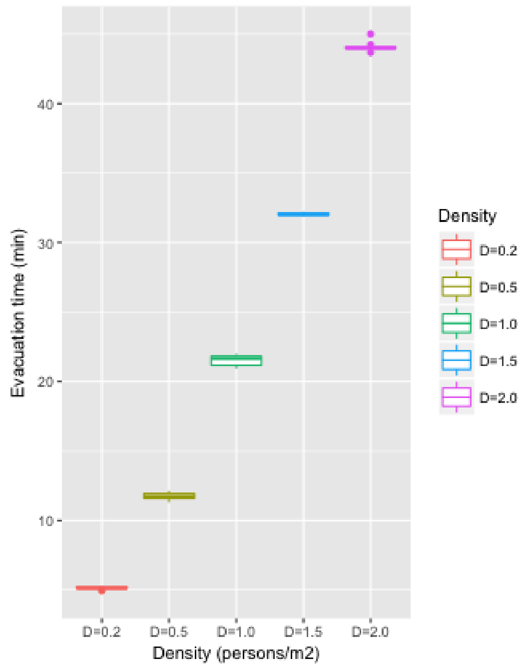


FIGURE 4.8: Impact of Density on Evacuation time

TABLE 4.5: Impact of Density on Evacuation time

Density (persons/m^2)	0.2	0.5	1.0	1.5	2.0
Mean Evacuation time (min)	5.14	11.72	21.52	32.05	44.09
SD(min)	0.112	0.277	0.388	0.091	0.352

well in the dotted line by using Rstudio. To test the fitted line, we conducted a t-test on these data. The output is shown in Table 4.6.

We conclude that increasing pedestrian density increased the mean evacuation time by an estimated 21.3717 (P-value < 0.0001). In conclusion, there was strong evidence that pedestrian density was associated with mean evacuation time. Therefore,

TABLE 4.6: T-test on the fitted line in RStudio

Situation	Estimate	Std. Error	t value	Pr>$\|t\|$
Intercept	0.6764	0.5674	1.192	0.319
Density	21.3717	0.4621	46.252	2.23e-0.5

the evacuation time can be obtained by pedestrians density in Equation 4.1:

$$y = 0.9036 + 21.1718x \tag{4.1}$$

Where: x : pedestrian's density (persons/m^2) y : Mean Evacuation Time (Minutes)

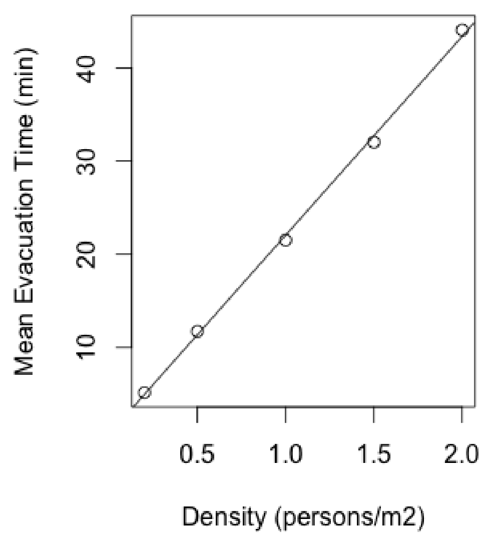


FIGURE 4.9: Impacts of Density on Mean Evacuation time

4.1.6 Effect of Smoke

To investigate how smoke affects the evacuation time, pedestrians arrival rate is applied to this experiment. Under this circumstance, pedestrian arrival rate in B1 floor is 1500 persons/hour without smoke and 750 persons/hour with smoke. As shown in Table 4.7, those SD are relatively smaller, which means these mean evacuation times can stand for these evacuation times. The mean evacuation time in no-smoke environment is 21.4 minutes, while smoke situation is 43.020 minutes, which is approximately twice than the former. It also proves Galea and Gwynne [96]'s conclusion that the situation with smoke doubled the evacuation time.

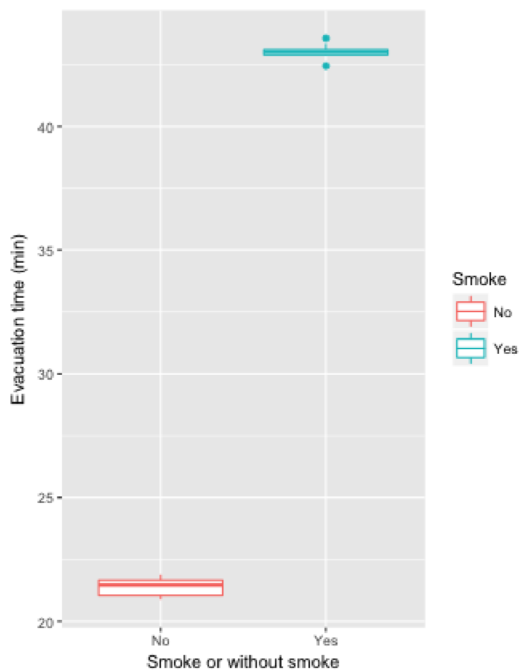


FIGURE 4.10: Impacts of Smoke on Evacuation time

TABLE 4.7: Impacts of Smoke on Evacuation time

Situation	Mean Evacuation time (min)	SD (min)
No Smoke	21.4	0.353
Smoke	43.020	0.296

4.2. Summary

This section is dedicated to understanding the general impact of critical factors on evacuation time in a given evacuation scenario. The results indicate that (1) ticket gate type play an important role in mitigating the congestion greatly but have little influence on pedestrian evacuation time; (2) it shows that there a non-linear relationship between evacuation time and walking speed, which also proves the theory that “faster is slower effect ”; (3) however, evacuation time is highly correlated with gender. Males tend to use less evacuation time than females; (4) similarly, pedestrian group size is of great importance for an evacuation scenario. When the density level fixed, with the growing group size, the evacuation time increasing rapidly; (5) in addition, pedestrian density is a positive correlated with evacuation time. The linear equation $y = 0.9036 + 21.1718x$ has been validated to fit the relationship; (6) for the smoke effect, the situation with smoke doubles the evacuation time. In the next chapter, several major findings will be concluded and summarized based on these results. The future research will also be provided in terms of minimizing fatalities and reducing economic loss caused by the underground emergency.

5. CONCLUSION AND FUTURE STUDY

5.1. Conclusion

This purpose of this thesis is to identify and validate the impacts of critical factors influencing the evacuation time and evacuation efficiency. Underground evacuation study in a given scenario was simulated with simulation software. Also presented was a detailed discussion for pedestrian evacuation under the conditions of different type ticket gates, different walking speeds, gender, different group size and different pedestrians densities. The research results are as follows: (1) Ticket gate type plays an important role in mitigating the congestion greatly, but has little influence on pedestrian evacuation time; (2) Walking speed has a non-linear relationship with evacuation time. When the walking speed is low (from 0.8 m/s to 1.0 m/s), the evacuation time will decrease as speed increases. When walking speed is high enough, large crowds will be assembled at the two ticket gates, which reaches the saturated evacuation status. That means with even though pedestrians walk very quickly, the evacuation time will increase as well. This phenomenon also supports the theory that "faster is slower effect "; (3) Gender is one of important factor influencing evacuation time. As expected, males tend to use less evacuation time than females; (4) Pedestrian group size is of great importance for an evacuation scenario. When the density level is fixed, with the growing group size, the evacuation time increases rapidly with growing group size; (5) pedestrian density is positively correlated with evacuation time. A linear curve and a relevant equation: $y = 0.9036 + 21.1718x$ between evacuation time and pedestrian density has been investigated to fit the relationship; (6) The situation with fire has a mean evacuation time approximately twice than that of a situation without fire. It also confirms that Galea and Gwynne [96]'s conclusion that the situation with smoke doubled the evacuation time.

5.2. Future Study

From the discussion above, we understand which factors contribute to the problem and how they affect the evacuation time. However, there are still some limitations and problems we should consider. In this section, future research is provided based on the current work.

5.2.1 Precaution and Evacuation Drills

As is discussed in the literature review, most accidents happened because of human factors. Therefore, it is extremely important to assure the safety of the subway or underground tunnel all the time. Most importantly, the governments and relevant departments should strengthen the security measures to avoid these accidents. In addition, relevant departments should frequently organize drills of evacuation for precaution, and encourage people to participate into the drills to practice. Huo [97] did an evacuation drills on an underground retail store and concluded that it was very important to move the obstacles nearby the emergency. Additionally, clogging places for evacuees should be far away from the exits.

5.2.2 Integration of Actual Human Behavior in Evacuation Modeling

Actual human behavior is complicated and very hard to predict in disaster. Hofinger and lauche [46] classified human factor to five levels: individual level, group level, organizational level, technological level, and system environment. In this case, it will be helpful to simulate and build a model and to do some empirical testings about human behavior at each level. For instance, for group level, people tend to gather together and communicate with each other, which might make people panic less and feel safer. Thus, this group level can affect human psychology but the movement might be slower than as isolated individuals.

5.2.3 Evacuation Facility Improvement

When an emergency incident occurs, the underground transportation systems will become a dim environment and lack appropriate light in many areas. People may panic in such an environment, which can lead to disorder and even lead to serious incidents. Light is one of the most important things when an accident happens. Therefore, these underground stations should have emergency lights in case of accidents and power failure. Meanwhile, fluorescent logo should be positioned on the stairs and floors which can be used for dissemination escape instructions. Zhao and Tang [12] mentioned that subway facilities should use noncombustible or flame retardant materials since these kind of materials can suppress fire spreading in stations.

5.2.4 Facilities for Disabilities

The previous literature rarely mentioned the evacuation processes and evacuation facilities for individuals with disabilities when fire incidents occurred in underground transportation systems. When the fire incidents happen, people tend to panic in darkness. It is worse for those with disabilities because they cannot move quickly. In Boyce et al. [98]'s study, they proposed that the speeds of locomotion disabilities were nearly 0.8 m/s on the horizontal and 0.33 m/s on stairs. Thus designers should consider this factor and take measures to help them, which will assure that everyone can evacuate when incidents happen. For example, designers should make sure there are sufficient widths for escape routes in underground tunnels. More research need to be done in this area. Zhao and Tang [12] discussed the concept about emergency shelter. They set up places for disabled people to have a temporary place to stay.

5.2.5 Self Rescue

The discussion about design problems mentioned above that is outside help. But in many situations, outside help comes too late. Thus self rescue is really important. Firstly, people should participate in relevant drills to get familiar with evacuation procedures, which will be helpful for self rescue. Furthermore, Kohl et al. [11] mentioned that people should know the safe area as quickly as possible. This “safe area”means emergency exit or cross-passage because these two places are rarely influenced by these incidents.

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