The influence of different bus stop types on movement of pedestrians involving disabled individuals: A microscopic pedestrian simulation using Agent-Based Modelling

Yunjing Hu

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University College London

Abstract

In order to create a high-quality public realm and promote better urban experiences, many cities have published street design guidelines covering various important aspects of street design from layout to construction details. However, how these influential elements can impact the movement and experiences of pedestrians needs to be further evaluated. Traditionally depended on observations and surveys, design evaluation can now be realised through simulation in a virtual environment. With the approach of agent-based modeling, a microscopic simulation model was built in this research to investigate the influences of four types of bus stops, which are bus flag, backing road, backing footway, backing building, on movement and experiences involving disabled individuals. In the model, walking and bus waiting behaviours were replicated based on the algorithm of social force model and experimented with different combinations of footway widths and pedestrian flows. Four collective features, average speed, density, delay time, and conflicts, were analysed as indicators of the movement quality. By statistical analysis, it turned out that the bus stop types involved are more likely to vary in influences on pedestrians when the footway is narrow and pedestrian flow is medium to high. In such situation, the results suggest that the bus flag allows pedestrian to move faster in a less crowded environment, and the bus stop backing footway does the opposite. Besides, the bus flag and backing building are less likely to create very different experiences in delay time and conflict incidents between disabled and non-disabled individuals. These findings confirm the possibility of applying such simulation in street design decisions. However, due to various limitations presented throughout the simulation and

analysis processes, further works in algorithm improvement, analysis elaboration, and model validation are also necessary to produce more realistic, useful, and informative results.

I, Yunjing Hu, hereby declare that this dissertation is all my own original work and that all sources have been acknowledged. It is 10,535 words in length.

Signature:

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List of Acronyms and Abbreviations

CA: Cellular Automata

SFM: Social Force Model

PV: Preferred Velocity model

PP: Preferred Velocity model

APP: Adaptive Preferred Velocity model

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1. Introduction

1.1. Context and Motivation

As an essential part of the public realm in a city, streets have always been a focus of policymakers, planners, urban designers, and engineers. Streets of high quality can play an active role in providing better services to people and improving the quality of life. To realise their visions on urban development and streets, many cities have published design guidelines to set standards for good street design that can indeed provide a satisfying user experience. For example, Streetscape Guidance has been updated to the fourth edition in 2019 by the Transport for London as a toolkit for relevant decision-makers to design safe, healthy and comfortable streets with a more solid basis. In New York City, the street design is guided by the Street Design Manual published by the Department of Transportation to follow the principles of Universal Design. Being one of the pioneer cities in China to do so, Shanghai has also published the Shanghai Street Design Guidelines in 2016 as a part of the more detailed instructions to realise the visions stated in the Shanghai Masterplan 2015–2040. In general, these guidelines aim to help decision-makers deliver a high-quality street design that is accessible, inclusive, safe, and sustainable.

In most of these guideline documents, the suggestions on street designs cover specification in all aspects about the street that can influence user experiences, from the lane layout to paving materials. However, the influence of certain designs or combination of some designs can vary in different scenarios. Thus, the effectiveness of these suggestions needs to be further evaluated. While the design evaluation traditionally depends on user surveys and on-site observations, this can now be accomplished through smarter approaches such as CCTV records and traffic simulation. In this paper, a prototype simulation tool will be built to evaluate the influence of certain proposed street settings on user experiences. With a special focus on bus stop types and by simulating pedestrian movement with agent-based modelling, this research is expected to figure out how different types of bus stands on the footway can affect the movement of pedestrians in the street.

1.2. Research Focus and Objectives

Based on the Pedestrian Comfort Guidance for London (2010), the bus stop type was chosen as the study target in this paper. Different bus stops are generally classified into four types in the guidance: bus flag, shelter backing road, shelter backing footway and shelter backing building. Thinking about the different sizes and positions of the bus stops, it can be imagined that different types may result in different pedestrian movements and interaction patterns. For example, the bus flag could be less congested than the shelter backing footway in a high pedestrian volume condition, since the bus flag takes less space and leaves greater clearance for people to move through. Also, the shelter backing building could lead to more pedestrian interactions than other types since the people boarding the bus from the shelter could interfere with the flow in the other direction. Thus, it is reasonable to assume that there is a specific relationship between the bus stop type and the pedestrian flow pattern.

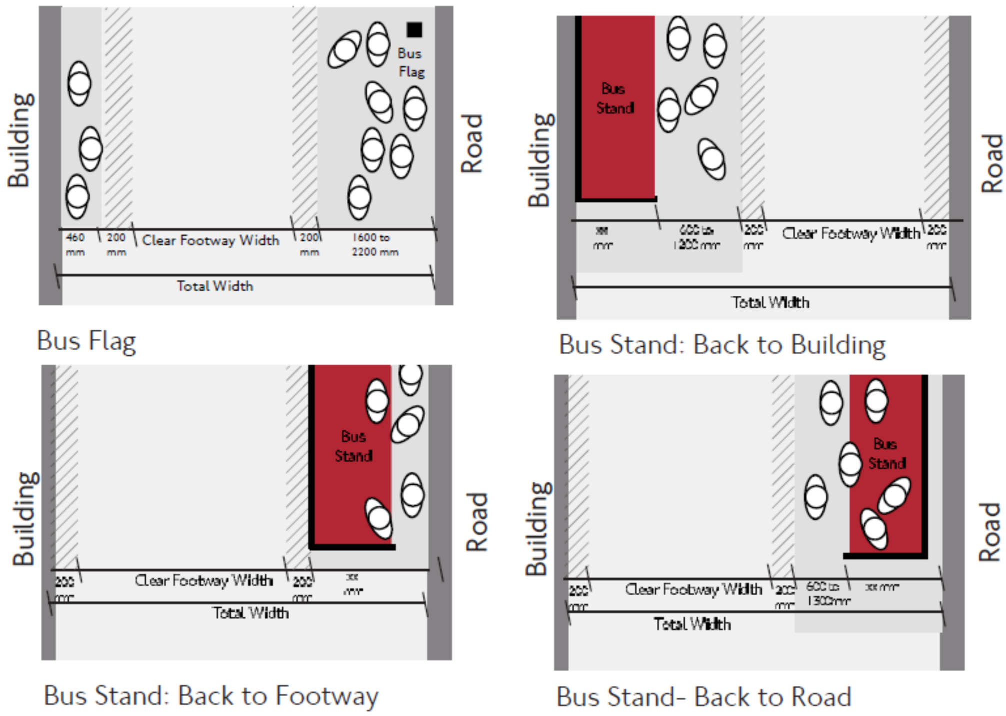

Figure 1 Four bus stop types listed in Pedestrian Comfort Guidance in London

However, pedestrian movement is a collective phenomenon formed by a group of independent and automated individuals, and it could be difficult to figure out the environmental influence on it through traditional observations and statistical analysis. In this case, it is suitable to study this dynamic system by simulating the pedestrian movement in a virtual world with agent-based modelling and conducting experiments in different environmental settings. Considering that the interested study range of the design environment is only limited to a segment of footway with street furniture, the simulation will be performed at a microscopic scale. Besides, pedestrians with disabilities will be involved in the simulation. The inclusion of individuals with mobility difficulties aims to better reflect the pedestrian group in reality and reveal how different groups can be impacted differently by the same setting.

The ultimate purpose of this research is to assess which type of bus stop causes fewer negative experiences among pedestrians in different street conditions. Then, the results can be used to support decision-making about the choices and arrangements for bus stops on sidewalks to promote smoother and more comfortable walking experiences.

To achieve the above purpose of design evaluation, the research is constructed to achieve the following two objectives:

1. Develop a prototype model that can microscopically simulate pedestrian movement in different design settings and record the characteristics of their movement.
2. Evaluate the impact of different types of bus stops on the movement and experience of pedestrians by analysing the simulation results.

2. Literature Review

To restate the research question of this paper, the research is to take the street settings and pedestrian behaviour as input, employ the approach of microscopic simulation, and examine the characteristics of the pedestrian movement produced as indicators of the quality of the street design. Therefore, the literature review has been conducted around the following two points of interest: the walking behaviour to be reproduced in the virtual world and the methodology used to realise the reproduction. This chapter will consist of two parts: real-world pedestrian behaviour studies and virtual world pedestrian simulation exploration.

1.1. Pedestrian Behaviour Studies

The study on pedestrian behaviour usually involves three key elements: the target behaviour to be analysed, the method or technology utilised to capture the behaviour, and the special settings or scenario in which the behaviours occur. Therefore, this section will be reviewed around these three parts.

1.1.1. The Behaviours

To analyse the pedestrian behaviour at an individual level, the essential step is to define the walking characteristics with selected measurable variables. Typical variables include the walking speed and comfortable spacing (Sharifi et al., 2017), while some studies also use gaze, i.e. the time spent looking at certain object (Fujiyama et al., 2007), gait, i.e. length and direction between steps (Hediyeh et al., 2015), or even heartbeat (Childs et al., 2007) to analyse movement. Perceived experiences, such as the level of anxiety and confidence, are also taken into consideration in some studies as evidence of external influences (Childs et al., 2007).

Besides, some classifiable behaviours can be of interest to the study as well, such as jaywalking (Lipovac et al., 2013; Wang et al., 2010) and negotiating behaviours between pedestrians and drivers at a crossing (Rasouli et al., 2018).

Since people vary in walking behaviour due to their personal abilities, pedestrians with mobility difficulties could walk and react to the environment differently from non-disabled groups. Meanwhile, with the issue of equal accessibility being more frequently discussed in urban design schemes, the walking characteristics of people with mobility difficulties have become one of the focal points of some research. McCarthy et al. (2015) assessed Alzheimer's responses to a visual cue using attachable sensors in laboratory experiments. Sharifi et al. (2017) recorded the walking speed and typical spacing of pedestrians with visual or mobile impairment in a controlled environment featuring situations of exit, doorway, passageway, right angle, oblique angle, and bottleneck. Pecchini and Giuliani (2015) surveyed disabled pedestrians at crosswalks and observed their crossing behaviours to record their walking speed and waiting time.

1.1.2. The Methods

The analysis of pedestrian behaviour cannot be realised without the use of various data collection methods and technologies. On-site observations (Basch et al., 2015) and in-person surveys (Childs et al., 2009) are traditional methods to collect behavioural data. Although they could be time-consuming to conduct and not precise enough when recording and calculate the walking speed, they are effective and necessary in gathering perceived feedbacks. Compared to field observations, pedestrian experiments in a controlled laboratory environment have given researchers more freedom to test and analyse the impact of different settings since they can better control other influential variables. With the experiment site set at a 1:1 scale to the real-world situation, Daamen and Hoogendoorn (2012) investigated the capacity of emergency doors with different widths. A laboratory experiment is also useful in assessing the impact of proposed designs which are yet to be installed in real world. Childs et al. (2007) experimented around various proposed delineators to assess their effectiveness in demarcating a safe area from a shared space environment for disabled pedestrians. However, due to limitations in participant sample size and composition, as well as the differences between a controlled experiment environment and the walking environment in the real world, the pattern summarised from the statistics may not be entirely consistent with the pattern in an everyday situation.

Nowadays, the development of technology has made more motions measurable and more precise capture of human movements possible. For instance, video tracking has been widely used to record walking speed, spacing, and other more complex behaviours (Sharifi et al., 2017; Hediyeh et al., 2015). Wearable or attachable devices have also been employed in many pedestrian experiments to capture behaviours at more accurate scale from head postures (Hasegawa et al., 2019), gaze (Fujiyama et al., 2007), or feet motion (McCarthy et al., 2015).

1.1.3. The Scenarios

Pedestrians' behaviours have been studied to understand how people react to certain environmental situations to reveal the kind of environment people move around in more easily. Therefore, most of the studies tend to focus on a specific scenario where the walking experience or efficiency is important. For instance, pedestrian behaviour at crosswalks (Deb et al., 2017; Basch et al., 2015; Hediyeh et al., 2015) and movement pattern in case of emergency evacuation (Daamen and Hoogendoorn, 2012; Heliövaara et al., 2012; Guo et al., 2012) have been widely investigated by researchers around the world. The human-environment interaction about more specific influential element has also been studied. Childs et al. (2009) experimented with different heights of kerb to figure out the sufficient height that is detectable for visually impaired pedestrians. Fujiyama et al. (2007) studied the effects of lighting conditions on the street hazard perception of the elderly. Since people may behave differently in special environmental conditions, such as walking at slower speeds or with more frequent checking behaviours, the research regarding such special conditions is necessary to provide a more accurate behaviour data and pattern.

Although studies on pedestrian behaviours in the real world could be cost-consuming and time-consuming to conduct, they are essential in gathering first-hand behaviour data and perceived feedbacks, which can be utilised as input in a virtual simulation. Besides, the possible impact of individual variation in body shape, intention, walking habit, etc., is also included and respected in studies involving real participants. Laboratory experiments are also useful in testing and assessing proposed infrastructural designs.

1.2. Digital Microscopic Pedestrian Simulation

Instead of studying individual pedestrian behaviours, pedestrian simulation is more of an approach to investigate the common movement patterns in different environmental settings using known individual walking characteristics. Existing pedestrian simulation research has generally focused on developing and improving algorithms to reproduce walking behaviours more accurately in the digital environment and applying the simulation results to support built-environment designs. Thus, this section will give an overview of classic pedestrian models, later elaboration of classic models, and typical applications of pedestrian simulation.

1.2.1. Microscopic Pedestrian Models

Pedestrian simulation can be achieved through agent-based modelling, a method able to model interactions between environments and automated individual parts (i.e. agents) through setting behavioural rules on agents (Gilbert, 2008). By this definition, although grounded in different theories to interpret walking behaviour, most pedestrian simulation models can be regarded as a kind of agent-based model. Two models have been widely employed to reproduce pedestrian motion in the digital environment: Cellular Automata (CA) and Social Force Model (SFM). CA is a grid-based model that simulates pedestrian movement in a discrete way. With CA modelling, the simulation environment is divided into cells being either empty or occupied, and pedestrians move according to a timed step to an adjacent unoccupied cell (Gipps and Marksjö, 1985). Although the simple rule can be an advantage of this model, it is also considered as its limitation since the discretisation of space and time can limit the possible directions and speed of pedestrians and make the moving trajectory not continuous as it is in reality.

The SFM allows simulated pedestrians to move in a continuous way. Originally developed by Helbing and Molnar (1995), SFM is analogous to the Newtonian mechanics in the way that pedestrian behavioural changes are driven by stimuli from one's environmental perception and personal aim, which makes the change automatic and predictable. Thus, Helbing and Molnar (1995) believed that the equation of motion could be used to represent the relationship between the temporary systematic changes of a pedestrian's preferred velocity and the stimuli, which is interpreted as a vectoral quantity called social force. According to SFM, three types of forces drive the walker together to move forward: his/her own will to reach the specified destination at the desired speed, the tendency to keep a distance from other walkers and some objects, and the attraction from some walkers and objects. This will force a function about the difference between the walker's current velocity and the desired velocity. The avoidance force, also called the repulsive effect, is dependent on the pedestrian's desired moving direction and the position difference between what to avoid. The attraction force is defined similarly to the avoidance force but is dependent on an additional variable of time.

Based on this concept, Helbing et al. (2000b) developed a continuum model simulating the bi-directional particle movement system in which the social forces on a particle were reorganised to be the will force, the repulsive interaction between other particles, and interaction between the boundaries. With the forces calculated, the acceleration of the particle can be known based on Newton's second law of motion. The authors later modified and applied this model to simulate features of escape panic in the bottleneck scenario. The modified version of the model took the body radius of pedestrians into consideration when calculating the repulsive effect and added two additional forces to represent the counteracting force and friction brought by body contact in a crowded situation (Helbing et al., 2000a).

1.2.2. Social Force Model Extensions

To make SFM more capable of representing human motion realistically, researchers have developed various extensions of the model to elaborate on the agent behaviours. Many extensions are aimed to improve the avoidance mechanism to increase the flexibility of agent movement. Cao et al. (Cao et al., 2017) integrated the idea of discretisation into SFM to allow agents dynamically change desired moving directions, which is represented by surrounding grids, according to a weighted choice model that evaluates the pedestrian speeds, crowd density, space occupancy, etc. With this extension, some pedestrian preferences for less occupied routes and lower speeds when passing by can be reflected in the simulation. Similar to this algorithm, Zhang et al. (2017) extended the model to allow agents to alter route adaptively to avoid potential moving obstacles by perceiving, weighting, and computing the movement of surrounding objects and agents. Another algorithm to prevent collision was proposed by (Gao et al., 2017), which modifies the desired force by taking the time headway and time before colliding into consideration.

Other modifications of SFM focuses on elaborating pedestrian behaviours. Yuan et al. (2017) introduced a gravitation force to interpret the following behaviour of pedestrians that people tend to adapt the moving directions and speeds to those of people who have similar motion status. The improved model is capable of better reflecting the line formation phenomenon in the channel setting. Besides, Johansson et al. (2015) extended SFM by modelling the waiting behaviour at transit stations with one of the three algorithms: the Preferred Velocity model (PV), the Preferred Position model (PP), and the Adaptive Preferred Position model (APP). These three models decide how agents adjust their desired speed and destination to reach the standing point after moving into the designated waiting area from a walking status controlled by basic SFM.

Compared to CA, SFM does not have the issue of the oversimplification of the environment of moving trajectory. However, the drawback of SFM is that the introduction of the force to represent human intention and behaviour could result in some unrealistic motions such as backward movement, body overlapping, and trajectory oscillation (Liu et al., 2014).

1.2.3. Scenario-based Simulation Applications

Similar to the aforementioned pedestrian behaviour studies, many pedestrian simulation kinds of research were also proposed to support emergency evacuation event or crosswalk infrastructure design. Lee et al. (2018) developed an evacuation simulation which included the perception and avoidance of spreading fire. Manley and Kim (2012) considered individuals with disabilities in their emergency evacuation modelling. Heliövaara et al. (2012) simulated the exit selection behaviour in the situation of corridor evacuation. Rouphail et al. (2005) investigated the influence of signal placement at roundabout crossing for blind people. Other than the above scenarios, researchers have also applied pedestrian simulation to larger scale urban design schemes. Anvari et al. (2015) built a model integrating pedestrian and vehicle movement, shortest route choice algorithm, and obstacle avoidance behaviour to simulate the traffic flow in shared space environment, aiming to help evaluate the suitability of shared space design against traditional street layout. Cao et al. (2016) simulated the crowd movement in Nanjing South Railway Station to discover the potential design problems, and the results have been used to successfully improve the infrastructural layout in the station for more efficient use of space.

1.3. Statement of Research Gap

To conclude the findings from the literature review, the study on pedestrian behaviour is necessary for understanding the impact of the environment on people. Pedestrian simulation can be a suitable tool to reveal and quantify this impact. Advanced in efficiency and flexibility, pedestrian simulation is capable of testing a large sample of pedestrians with great attribute variation and evaluating different proposed design plans before they are carried out. However, current applications of pedestrian simulation in design optimisation have only focused on limited scenarios, including evacuation and crossing. The pedestrian composition was also not always considered in the existing simulations, that is, agents with different abilities and walking characteristics might not be included. Therefore, there is great opportunity to develop new modifications of the pedestrian model with agent types and settings that have not been discussed yet. In this case, with the inspiration from existing street design guidelines, it is proposed to experiment with the pedestrian simulation model involving disabled agents and sidewalk design in this paper.

2. Methodologies

2.1. Model Construction

To achieve the purpose of this research, an agent-based model was constructed based on the algorithm of SFM to investigate how pedestrian movement patterns differ on a segment of the footway with different types of bus stops. That is, with the bus stop type and individual walking characteristics set as inputs, the model can simulate a collective pedestrian movement pattern and quantitatively present the key features of the pattern. In order to explain the mechanism of this model, this section will introduce the structure of the model in an up-down way.

In general, built with the NetLogo software, the model is composed of three modules: initialisation, simulation, and evaluation. The initialisation part sets up the environment and creates agents as desired. Then, the simulation part moves every agent to the new position by computing the position change happening at each time step using SFM formulas. Finally, the evaluation part reports statistics indicating the movement quality of the overall pedestrian flow. To be more specific, the following paragraphs will dissect each module to show how the model works.

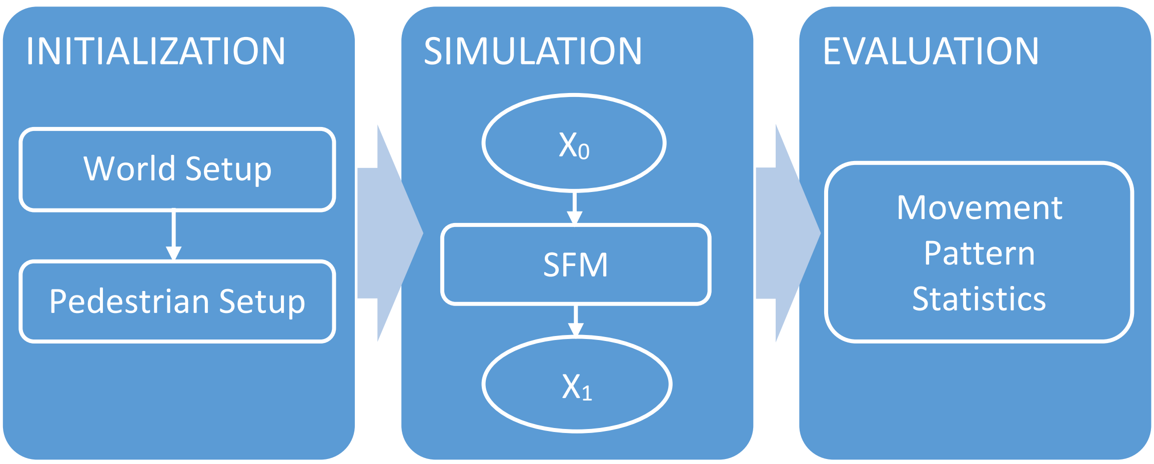

Figure 2 Model framework

3.1.1. Initialisation

For initialisation, input variables about the agent and environment will be set up. Since the pedestrians in this research include individuals with disabilities, the walking characteristics and some personal traits including the desired walking speed, sense radius, comfort zone radius (i.e. desired spacing), mass, and body radius of each agent vary with pedestrian ability. Agents also differ in their purpose of trip, which means that some of the pedestrians are assigned to wait for the bus while others aim to reach the other end of the footway. Besides, to test the sensibility of the model in various conditions, pedestrian flow amount is also designed to be adjustable. As for the environment, it will be set with a grid-based 2D plane with limited height and width representing a segment of the footway, where the position and shape of bus stops and waiting area will be represented by designated cells.

Table 1 Independent variables used in the model

Variables	Value	Unit
Environment		
footway width	4/6/8	meter
bus stop type	backing road	
	backing footway	
	backing building	
	bus flag	
pedestrian flow	500/1000/1500	people per hour (pph)
waiting area	True or False	
Pedestrian		
ability	non-disabled	
	motorized wheelchair	
	non-motorized wheelchair	
	visually impaired	
desired speed	varies with ability	m/s
sense radius	varies with ability	meter
body radius	varies with ability	meter
mass	varied with ability	kg
comfort radius	varied with ability	meter
whether the pedestrian goes for the bus	True or False	

3.1.2. Simulation

Functioned as the core of the model, the simulation module is composed of commands controlling the agent motions, which can be divided into three stages: define behaviour, calculate forces, and make movement.

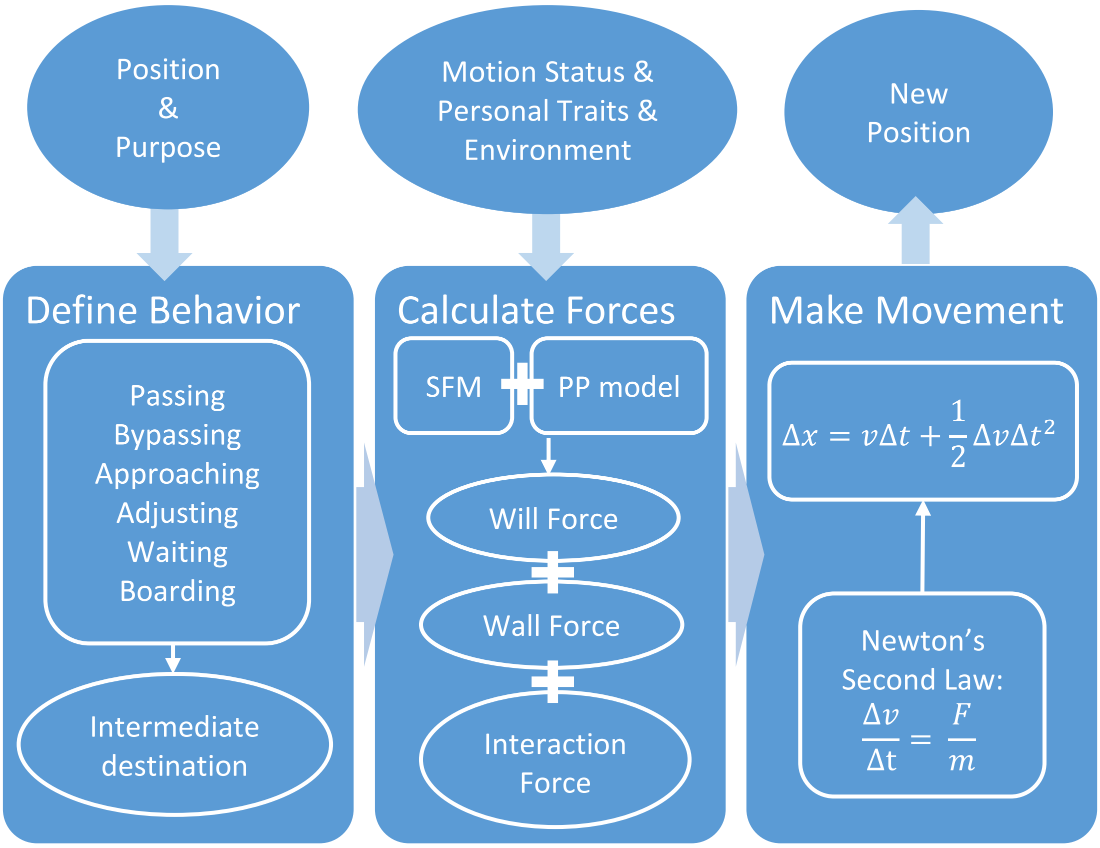

Figure 4 Simulation process framework

First, since the agents vary in purposes of the trip and thus, the desired moving directions, a decision choice model was designed to decide the agents' current behaviour mode based on its final purpose and current position. In general, agents not coming for the bus will be defined as 'passing' at the beginning and have their destination as the closest point on the other end of the channel. If the bus stop is in the way and within a certain distance, the agent will switch to 'passing by' and take a detour to avoid running into the bus stop. For agents coming for the bus, they will change their behaviour mode dynamically depending on their current position. Before entering the waiting area, the agent will have the mode of 'approaching' with the intermediate destination set as the closest patch in the waiting area. Once in the waiting area, the agent will be assigned a preferred waiting point randomly selected from available patches within the waiting area and switched to the mode of ‘adjusting’, or to ‘waiting’ if they have already reached waiting point. Besides, a portion of agents waiting for the bus will change to the ‘boarding’ mode at a fixed frequency, mimicking the event of bus arrival, and move to a designated point on the edge of the footway.

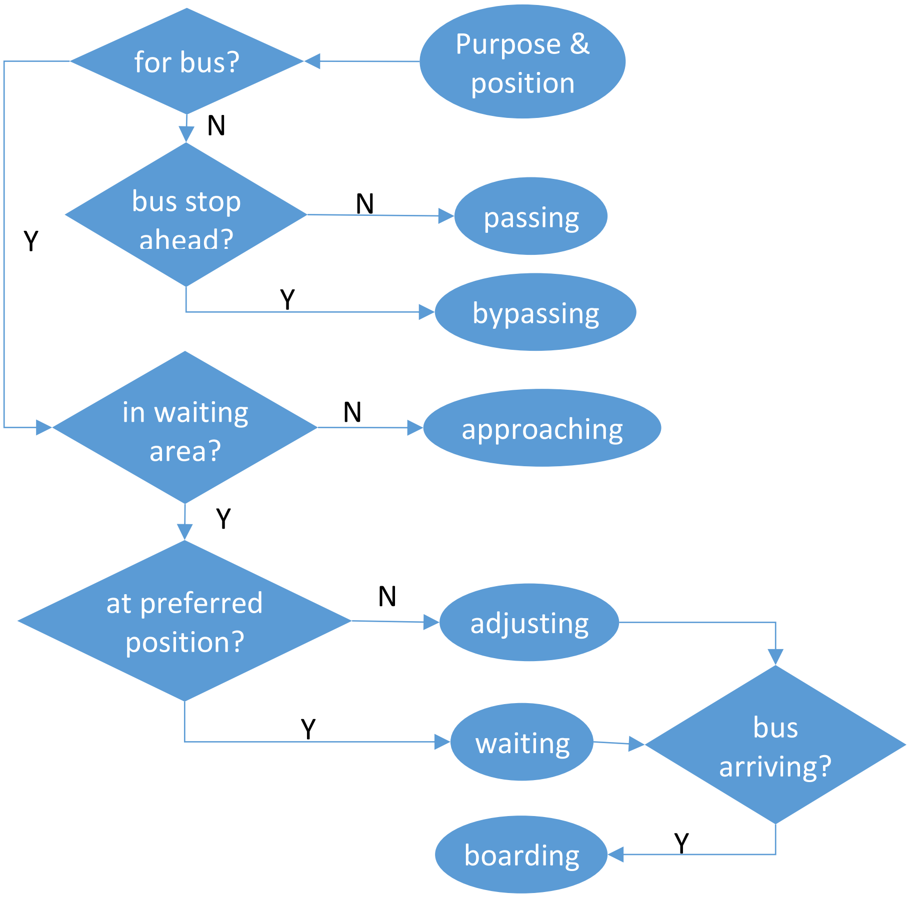

Figure 5 Flowchart for behaviour defining model

The second stage calculates the social forces for the agents after knowing the behaviour mode and intermediate destination at the moment. The model used for the calculation varies with the agents’ behaviour mode. The motion of pedestrians with behaviour modes other than ‘adjusting’ will be controlled by Helbing et al.’s (2000a) SFM. The total social forces occurring on an agent can be expressed as

$$F_{total} = f_{will} + \sum_{j(\neq i)} f_{ij} + \sum_{i} f_{iW} \tag{1}$$

In the equation (1), f_{will} denotes the will force, $\sum_{j(\neq i)} f_{ij}$ denotes the sum of interaction forces coming from other pedestrians within a certain sensible range, and $\sum_i f_{iW}$ denotes the sum of wall forces that keeps agents away from any boundaries or edges. More specifically, the will force is calculated based on

$$f_{will} = m\frac{v^0(t)e^0(t)-v(t)}{\tau} \tag{2}$$

While m and τ are two constants standing for the mass of the pedestrian and a relaxation time set as 0.5 seconds, $v^0(t)$, $e^0(t)$, and $v(t)$ denote the desired speed, desired moving direction, and actual velocity at time t. Then, the interaction force from one other pedestrian j on pedestrian i and the wall force are defined as

$$f_{ij} \ = \left\{A_i \exp\left[\frac{r_{ij}-d_{ij}}{B_i}\right] + \mathrm{kg}\big(r_{ij}-d_{ij}\big)\right\} n_{ij} + \kappa g(r_{ij}-d_{ij})\Delta v_{ji}^t t_{ij} \tag{3}$$

$$f_{iW} \ = \left\{A_i \exp\left[\frac{r_i-d_{iW}}{B_i}\right] + \mathrm{kg}\big(r_{ij}-d_{iW}\big)\right\} n_{iW} + \kappa g(r_{ij}-d_{iW})(-v_i t_{iW}) t_{iW} \tag{4}$$

The two equations above have the same structure – the first half stands for the repulsive force and the second half stands for the friction. r_{ij} denotes the sum of body radius of the two interacting pedestrians, and d_{ij} or d_{iW} denotes the distance between the mass centre of two pedestrians or the distance to the wall. n_{ij} represents a normalised vector pointing from pedestrian j to pedestrian i, and n_{iW} means the direction perpendicular to the wall. t_{ij} means the tangential direction and Δv_{ji}^t means the tangential velocity difference between two pedestrians. Similarly, t_{iW} means the tangential direction between the pedestrian and the wall, and $-v_i t_{iW}$ means the velocity difference from the pedestrian to the wall at tangential direction.

Besides, A_i, B_i, k, and κ are constants set to be 2×10^3 N, 0.08 m, 2.4×10^4 kg/s^2, and 1 kg/(m·s) according to Yuan et al. (2017). The function $g(x)$ is defined as

$$g(x) = \begin{cases} 0, & r_{ij} < d_{ij} \\ x, & r_{ij} \geq d_{ij} \end{cases} \tag{5}$$

For those defined as 'adjusting', instead of using the value set at the initialisation step, the desired velocity at each time step will be computed using Johansson et al.'s (2015) PP model, which changes dynamically with the distance to the preferred waiting point. The relationship between the temporal desired velocity v^{pw} and preferred position can be summarised as

$$v^{pw}(X) = \begin{cases} v^0(X^{pw} - X)/d, & |X^{pw} - X| \leq d \\ v^0(X^{pw} - X)/|X^{pw} - X|, & |X^{pw} - X| \geq d \end{cases} \tag{6}$$

X denotes pedestrians' current position, and X^{pw}, the preferred waiting point. d is set to be $2v^0/m$ in this model. The new desired velocity calculated here will replace the $v^0(t)$ in equation (2), and the rest of the calculations on social forces will remain the same as stated.

After the social forces on the agents have been calculated with known purpose, position, current velocity, desired velocity, and attributes of any interactive agents or objects, the simulation process can move to the third stage. According to Newton's second law of motion, the acceleration of an agent can be calculated by

$$\mathrm{a} = \frac{\Delta v}{\Delta t} = \frac{F_{total}}{m} \tag{7}$$

Thus, the new position X_1 of the agent can be known:

$$X_1 = X_0 + \frac{1}{2}(2v + \Delta v)\Delta t \tag{8}$$

3.1.3. Evaluation

Finally, the evaluation module calculates and displays the outputs of the simulation, which are four features selected to be compared among generated movement patterns: the average speed of pedestrians, the pedestrian density, conflict incidents, and mean delay time. The pedestrian density is calculated by the number of agents divided by the area of the simulated footway, which is 30m × the footway width. The conflict incident refers to circumstances where there are other pedestrians within the range of one's comfort radius ahead. The model records the total number of such circumstances occurring during the entire trip for agents outside of the waiting area. Pedestrians within the waiting area are not included in this process because it is believed that people tend to be more tolerant about the minimum distance from others while standing or moving slowly within a space with limited room. Lastly, the mean delay time is the extra time an agent consumes to complete the trip compared to the minimum time needed if moving at the desired time and route at all times. Thus, the mean delay time of those who complete the trip is calculated as a collective feature of the overall pedestrian movement.

2.2. Experiments

2.2.1. Independent Variables

A series of experiments were designed to study how the movement patterns differ with variations in the environment and pedestrian settings. The environment variation comes from different footway widths and bus stop types. The footway is set to have a length of 30 metres and a width of 4, 6, or 8 metres. There are four bus stop types: the bus flag, shelter backing road, shelter backing footway and shelter backing building. As mentioned in the introduction section, they are shaped and positioned according to what is depicted in the Pedestrian Comfort Guidance for London (2010). However, due to the limitation of the raster visualisation environment of the simulation tool, in which the length of each cell represents 0.5 metres in the real world, the dimensions of the bus stops were approximated. Therefore, the bus flag, represented by a single cell placed 0.5 metres away from the footway edge, takes up the space sized 0.5 * 0.5 metres. All other types have a length of three metres and a width of 1.5 metres but positioned and oriented differently. Varied with the bus stop types, the range of the waiting area will also slightly change from case to case, which is annotated in figure 7 below. In the view window of Netlogo interface, the upper grey edge represents the driveway, lower edge represents the building, and the white space in between is the footway. In addition, red cells represent the space taken by bus stands, and yellow cells define the waiting area.

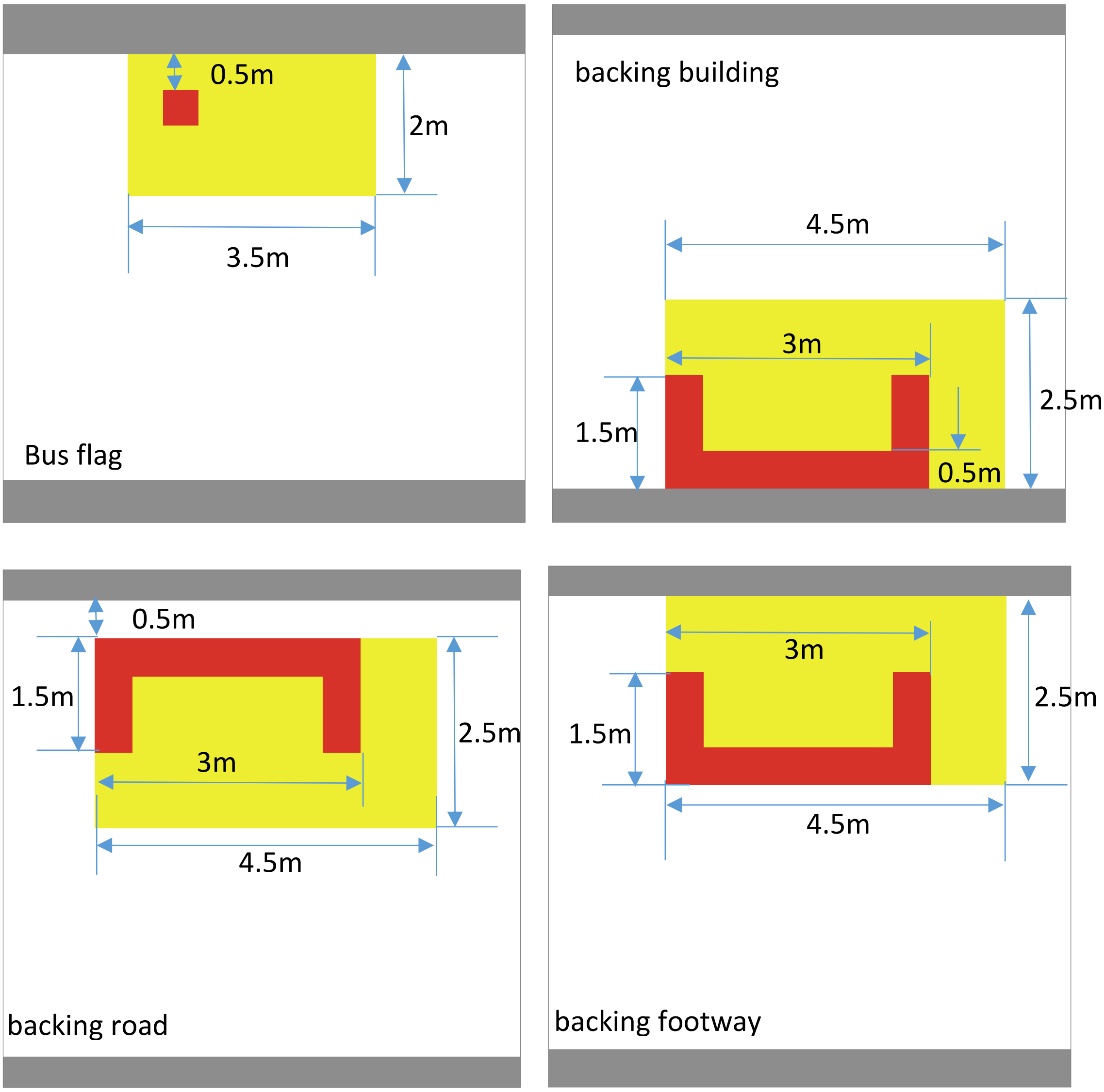

Figure 7 Bus stop visualization in Netlogo

For variations in pedestrian settings, the pedestrian flow can be set within the range of 100 to 1800 people per hour (pph), standing for the number of people passing a certain line per hour. The pedestrian composition, which refers to the percentage of each category of disabled individuals, can also be adjusted in the range of 1% to 10%. People with different abilities will have their mass, body size, desired speed, and spacing set differently. One's desired speed and spacing values will be selected randomly based on a normally distributed possibility and bounded within the range of one standard deviation away from the mean value. The data used for this setting was taken from Sharifi et al.'s (2017) pedestrian laboratory experiments in which the mean and standard deviation of speed and spacing were summarised for pedestrians with different abilities and walking auxiliary tools at different environment situations. The data used here is those recorded in the situation of walking through the passageway, which is closer to the simulating environment in this research.

Table 2 Input pedestrian walking characteristics

Ability	Desired speed (mean/std)	Body radius	Sense radius	Desired spacing (mean/std)	Mass
Non-disabled	1.12/0.16	0.25	0.7	1.52/0.4	65
Motorised	0.78/0.21	0.4	0.7	1.73/0.37	100
Non-motorised	0.68/0.17	0.4	0.7	1.68/0.31	100
Visually impaired	0.97/0.23	0.25	0.4	1.39/0.43	65

2.2.2. Experiment Settings

Arranged with the BehaviorSpace tool in NetLogo, two sets of experiments about the performance of four types of bus stops in different conditions were conducted. During the experiments, for each combination of settings, the simulation was repeated 10 times for 36,000 time steps, each of which represents 0.005 seconds. This length of time, which represents three minutes in reality, was chosen to leave enough time for the phenomenon emergence and for the accumulation of adequate pedestrians to make the layer statistical analysis meaningful. The proportion of each disabled group was set to 5%; thus, a total of 15% for all types of disabled groups in all simulations.

The first set of experiments were designed to reveal how the movements change over time and how the overall pedestrian experience was after the 3-minute simulating period. Thus, the experiments recorded the average speed, density, mean delay time, and total conflict incidents every 200 ticks. Besides the overall mean delay time and total conflicts, the mean delay time and mean conflict incidents on disabled and non-disabled groups were also calculated respectively. These were included to compare the possible influence of differences on different groups. The simulations were run with six combinations of pedestrian flow and footway width. The six combinations are a flow of 1,500 pph on the footway with all three available widths, a flow of 1,000 pph on the 4-metre and 6-metre footways, and a flow of 500 pph on the 4-meter footway. The settings were arranged to represent situations of high, medium, and low levels of pedestrian flow on narrow, medium, and wide footways. In this case, situations of low flow on medium and wide streets and medium flow on wide streets were excluded because it can be imagined that when the footway is spacious enough for only a limited number of pedestrians, the influence of a bus stop shelter would not be significant.

The second set of experiments explored sensibility of each bus stop setting to pedestrian flow increase – how the mean delay time and total conflict incidents at the end of simulation change with pedestrian flow ranging from 100 pph to 1800 pph, with intervals of 100. The combinations of each pedestrian flow value and the four types of bus stops were tested on three levels of footway width, and the outputs were recorded at the end of each run.

2.3. Analysis

The experiments output a series of CSV tables to be used in the statistical analysis. Accomplished through Python scripts, the statistical summaries and figures were organised in such a way to compare the four selected features between the four bus stop types with different controlled variables. Since the simulations on each setting combination have been repeated 10 times to reduce the effect of stochastic settings in the model, the mean and standard deviation of the 10 results were calculated to represent the result of each setting combination. The time-speed plots were produced to compare the emergence patterns of the average speed in different width-flow combinations. A bar chart summarising the final status of the average speed was also plotted to clearly illustrate the differences between the scenarios. The density was analysed in the same way as the average speed with a time-density plot and bar chart focusing on the trend of change and possible natural status, respectively.

As for the mean delay time, the emergence pattern of this feature was not analysed, since the calculation of a mean value requires a significant number of samples to be meaningful. However, the agents included in this calculation did not start to accumulate until a certain intermediate point of a run, and there could be a very limited number of effective agents especially in low flow situations. Other than this, the mean delay time at the end of the simulation was compared among width-flow combinations and between disabled and non-disabled groups. Three flow-delay plots were also created to reveal the influence of flow increase on the mean delay time at different street width conditions. Finally, the total conflict incident was compared in all three aforementioned ways in a time-conflict plot, flow-conflict plot, and bar chart. The influence on conflict incidents was also compared between disabled and non-disabled pedestrians, but using the mean number of incidents calculated at the end of a run, since the number of agents in the two groups were different.

4. Results

4.1. Average Speed

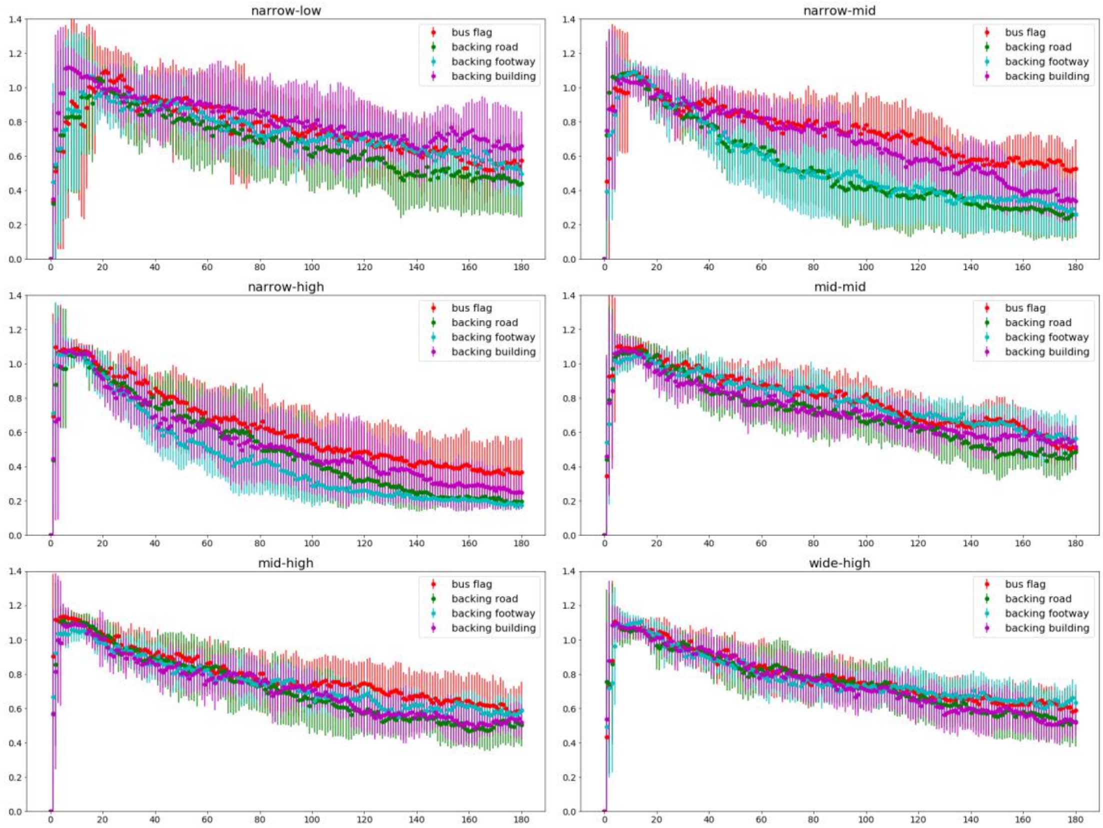

Figure 8 speed-time plots

The trend of how the average speed of the pedestrians currently in the simulation environment changes over time in the different width-flow settings is illustrated in the time-speed plot above. The x-axis represents time in seconds, and the y-axis, the speed in m/s. The dots mark the mean values of results from 10 simulation replicates, and the error bars represent the amount of one standard deviation away from the mean value. Overall, the trend is the same with all the bus stop types in all width-flow settings – after a short stage of pedestrian acceleration, the average speed gradually decreases from around 1.1 m/s. The rate of the speed decrease lowers over time as well, so the average speed tends to reach a stable state at the end of the simulation.

However, this change over time emerged in different ways between bus stop types and among scenarios. The speed varies more between bus stop types in the narrow street situations where the lines are more apart from each other, while in the medium and the wide street situations the lines are twisted together almost all the time. In both narrow-mid and narrow-high scenarios, the lines representing bus flag and backing building have higher average speeds than those of backing road and backing footway in general, and the variance tends to be more obvious during the latter half of the simulation. Meanwhile, in a narrow-low scenario, though not as clear and apparent as the pattern of the other two narrow street scenarios, a similar difference exists, in that the backing building type has a slightly higher average speed while the backing road has a relatively lower speed.

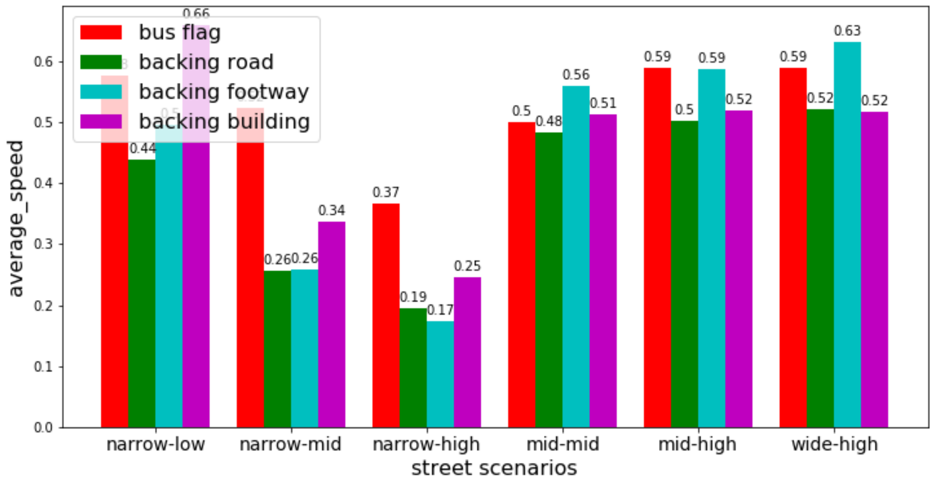

Figure 9 Final average speed

The bar chart above compares the final average speed between each scenario. The figure indicates that in all the narrow street scenarios, the final speed is always higher with the bus flag and backing building types, especially for the bus flag in narrow-mid and narrow-high scenarios. In those two scenarios, the final speed on the footway with the bus flag type is 0.52 m/s and 0.37 m/s, respectively, which is about twice the speed on the footway with backing road and backing footway types. The medium and wide street scenarios share the same pattern in that the speed of bus flag and backing footway is always slightly higher than that of the other two bus stop types. The speed of the backing road and backing building is very close to each other and keeps around a value of 0.5 m/s in all three scenarios.

4.2. Pedestrian Density

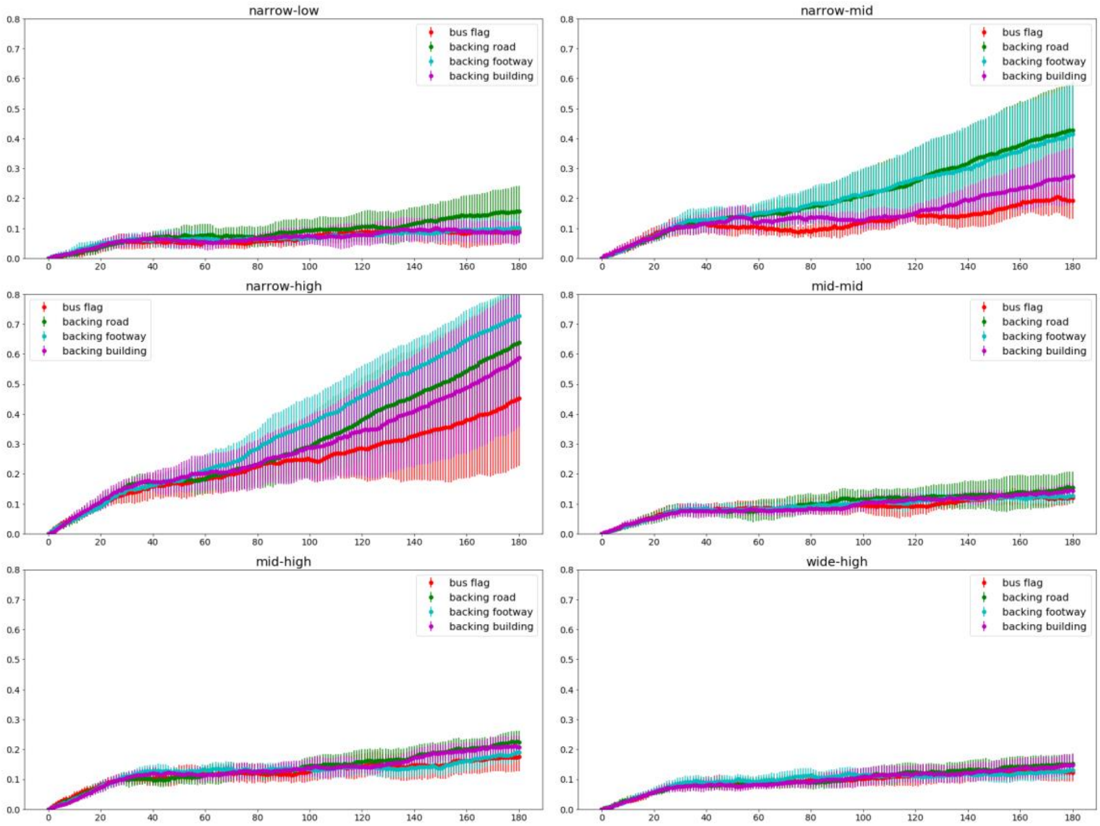

Figure 10 Density-time plots

Similar to the format of the time-speed plot, the time-density plot illustrates the change of pedestrian density over time, with the y-axis representing the density in the unit of people per square meter. As a general emergence pattern appeared in all scenarios, the density gradually increased over time. However, the rate of increase, indicated by the gradient of the line, lowers at a changing point, which is around 30 seconds after the start of the simulation. Since the rate of increase seemed to be consistent after the changing point, the density kept increasing and did not show signs of reaching any stable status during the time of the simulation.

In any of the width-flow scenarios, the density was almost identical in all bus stop type situations before the changing point, after which the differences caused by bus stop types emerged. Such variations are consistent with the findings on average speed, which means that the density generated through different bus stop types varies more in the narrow street situations than in the other three scenarios. Among the three narrow street scenarios, the density is bigger and has a greater range when the flow is higher. This can clearly be perceived from the bar chart displaying the final density at the end of the simulation. When the pedestrian flow is low, the density difference is not obvious that only the backing road type has a slightly higher density than other types during the simulation time. When the flow is at a medium level, the final density ranges from 0.19 to 0.43, with the bus flag being the least and the backing road being the most, and the backing footway generally had a similar density with the backing road throughout the entire simulation. At a high flow level, the density ranges from 0.45 to 0.73, completely higher than those of medium flow. In this situation, there is a clear rank of the final density, with backing footway being the highest, followed by backing road, backing building, and bus flag.

As for the medium and wide street situations, it can be seen from the figures that the density values and rate of increase are generally the same for all the bus stop types. There are only minor differences between the bus stop types in final density for medium and wide street scenarios, and the statistics are almost the same in mid-

mid and wide-high situations, with the final densities ranging from 0.12 to 0.15 while the mid-high scenario has slightly higher numbers ranging from 0.17 to 0.2.

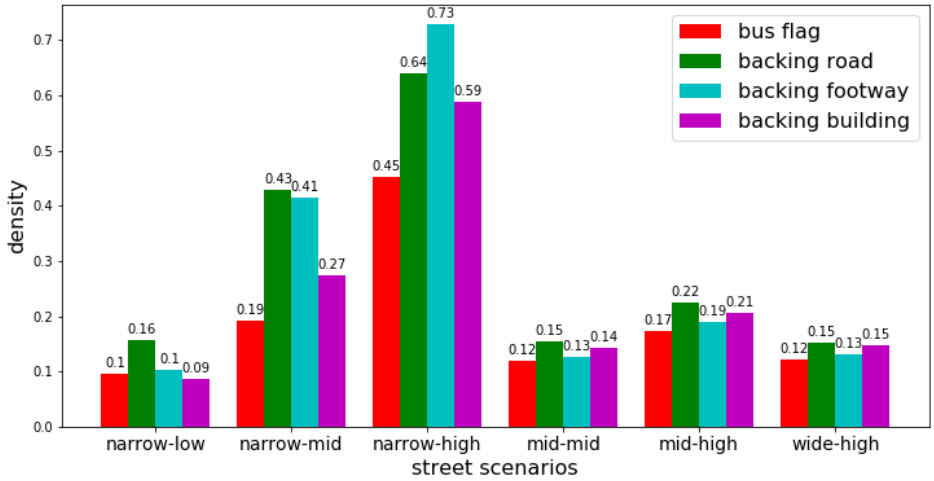

Figure 11 Final density

4.3. Mean Delay Time

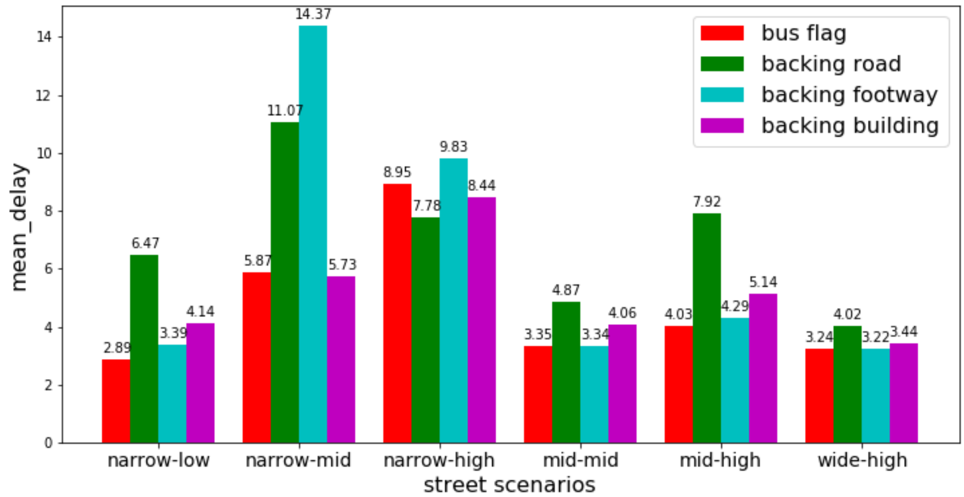

Figure 12 Final mean delay time

As previously stated, to guarantee enough samples, the mean delay time will only be examined by the final result of the simulation, which is the average extra seconds taken to go through the footway by all pedestrians who already finished the trip during the 3-minute simulation period. Although the general differences between narrow and wider street situations found in the average speed and density do not appear again here, the bar chart still displays three major findings worth noticing.

First, among the six width-flow combinations, the narrow-mid and narrow-high are more likely to cause a higher mean delay time. In the narrow-mid scenario, there are especially high values of 11.07 and 14.37 seconds when the bus stop is the backing road and backing footway types, while the number has never exceeded 10. Meanwhile, in the narrow-high scenario, the four types of bus stops have similar performance leading to the mean delay time ranging from 7.78 to 9.83, which is generally larger than almost all other situations. Second, the mid-mid and wide-high scenarios have fewer variances between the bus stop types and shorter delay times in general compared to other scenarios. Third, the backing road bus stop seems to be more likely to cause longer delay times. It is very noticeable that the mean delay time of the backing road is almost twice as much as that of other types in narrow-low and mid-high scenarios, and it is also the largest in mid-mid and wide-high scenarios.

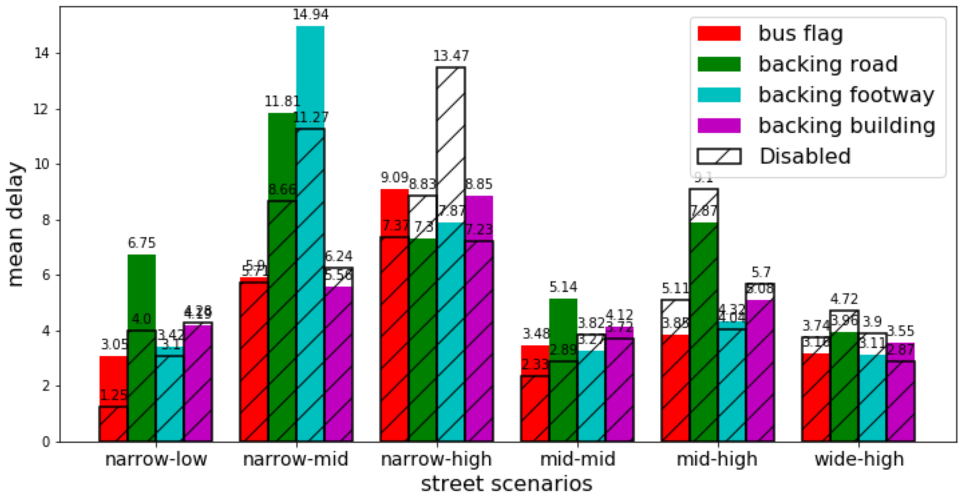

Figure 13 Comparison of final mean delay time between disabled and non-disabled groups

To investigate whether people with or without disabilities have been influenced differently, the mean delay time was calculated separately for the two groups, and the bars representing the delay time of the disabled were plotted on top of the non-disabled for a clearer comparison. Looking at the bars for each group separately first, some of the previous findings are still valid. For both pedestrian groups, the narrow-mid and narrow-high have longer delay times compared to other scenarios, and mid-mid and wide-high have smaller and fewer variant values. In a comparison of the differences between the two groups, it can be seen from the figure that a regular pattern of the differences, such as one group always having less mean delay times, does not seem to exist. The backing road bus stop is likely to cause longer mean delay times in the non-disabled group, but this is not seen in the disabled group. Besides, the backing footway has led to a relatively greater difference in the mean delay time between the two groups in the narrow-mid and narrow-high scenarios.

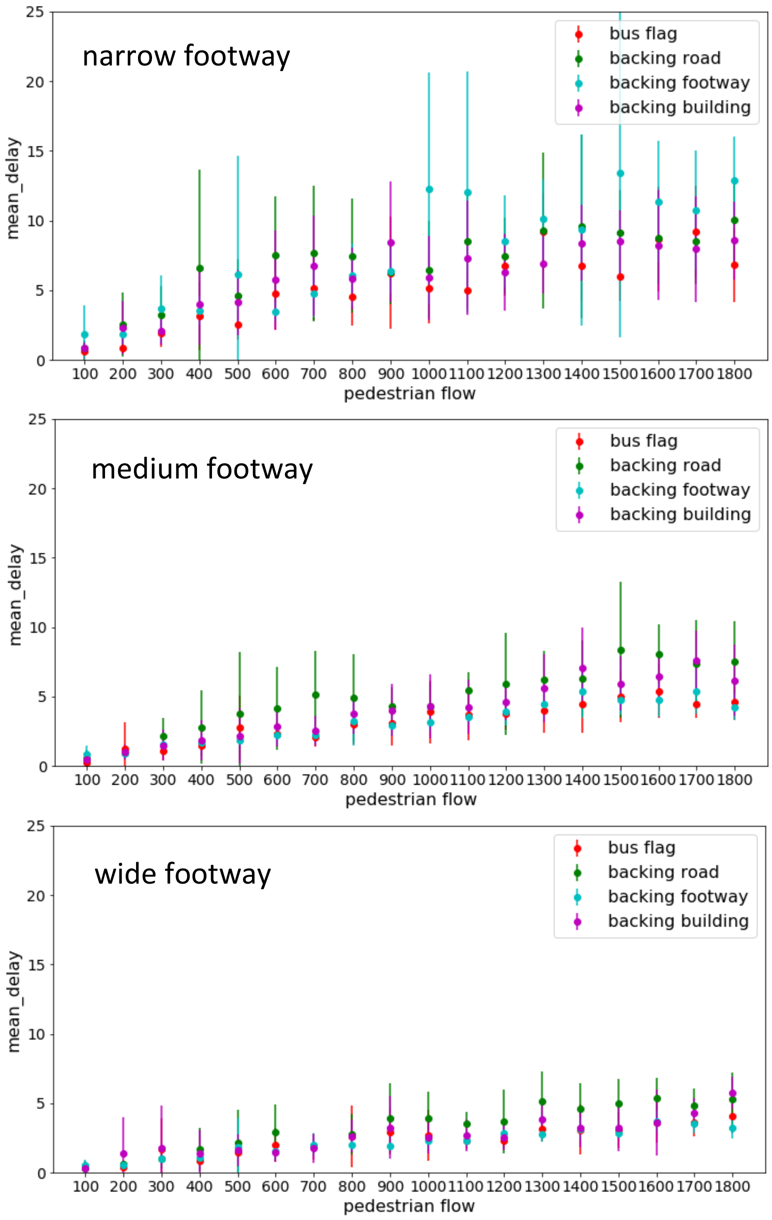

Figure 14 Delay-flow plots

The three scatter plots depict how the mean delay time changes with pedestrian flow ranging from 100 to 1800 pph in the three footway width levels. In general, there is a positive correlation between pedestrian flow and mean delay, but the increase in flow has less impact on the mean delay time increase on wider streets. It is clearly seen that the gradient of the implied lines on the narrow street plot is greater than that on the wide street plot. The variance between the bus stops is more obvious on the narrow street as the dots are separated, and the backing footway seems to be more positively correlated with the pedestrian flow.

4.4. Conflict Incidents

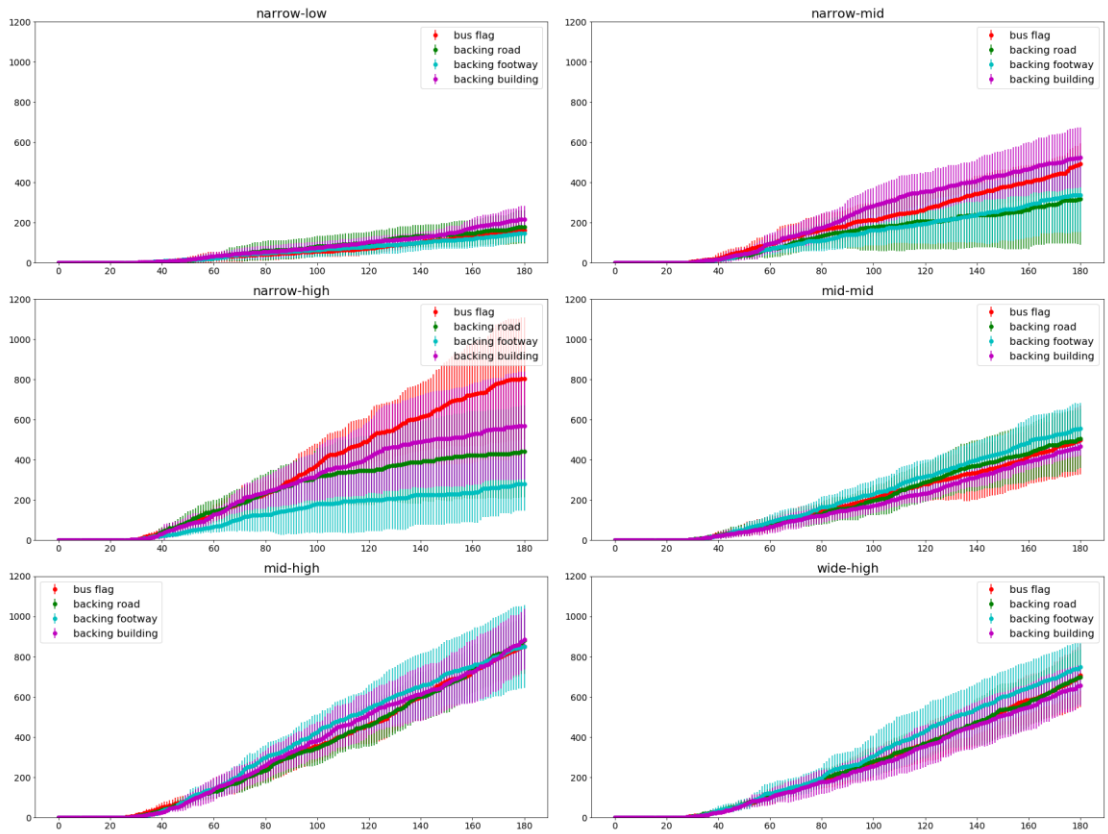

Figure 15 Conflict-time plots

The subplots above demonstrate the accumulation of conflict incidents over time in different scenarios. Since this is an accumulative feature, it is bound to increase over time and with higher pedestrian flow. Therefore, the comparison will focus on the differences between the bus stop types. Again, the variance among the bus stop types in the emergence pattern is minor when the flow is low, or the footway is not narrow. In the narrow street situations, the different bus stops become more obvious when there is more pedestrian flow. In the narrow-mid scenario, backing building is the fastest in conflict incidents accumulation, followed by bus flag and the other two. In the narrow-high scenario, the backing footway is the slowest in conflict incidents accumulation all the time. Meanwhile, the other three had nearly the same accumulation rate during the first half of the simulation, while after the midpoint, bus flag became the fastest, followed by backing building and backing road.

By looking at the bar chart recording the total conflicts accumulated during the entire simulation process, there are two other findings worth noticing. First, with the same pedestrian of 1,500 pph, wider footways do not necessarily lead to fewer incidents of conflict. As the figure shows, though the wide footway generally has smaller numbers of incidents than the medium width footway, the narrow footway has the least incident records for all bus stop types except bus flag. Second, when the footway is narrow, the backing footway has significantly fewer conflict incidents compared to other types. In particular, the number of backing footway is only 60% of the number of bus flag in narrow-mid scenario and less than 40% in narrow-high scenario.

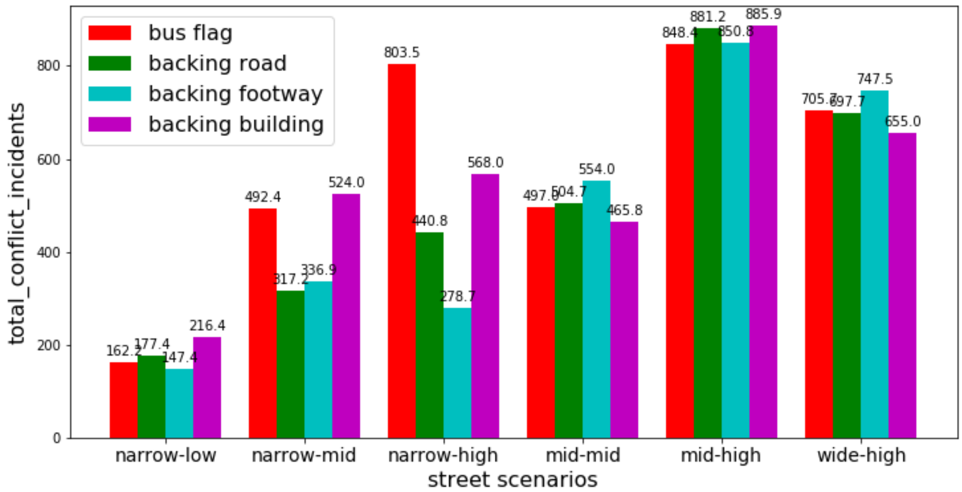

Figure 16 Final total conflict incidents

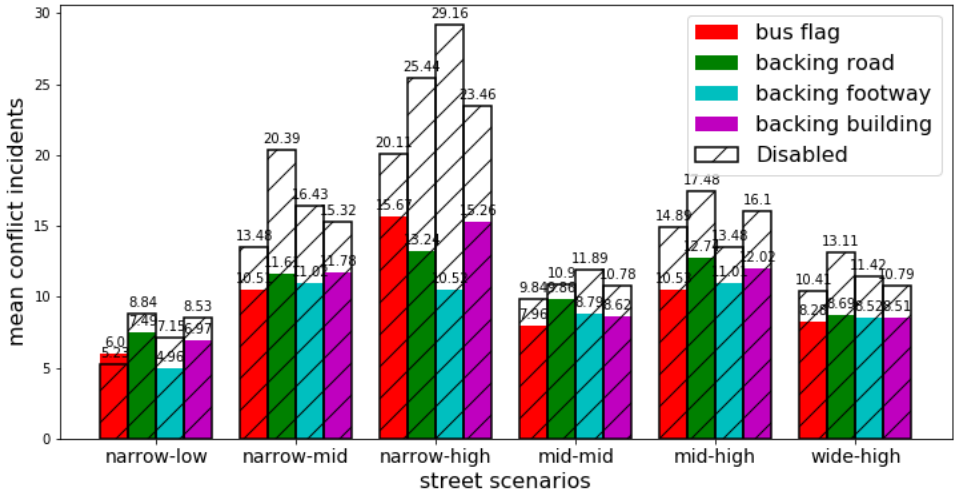

Figure 17 Comparison of mean conflict incidents between disabled and non-disabled groups

Coming to the comparison of conflict incidents that happened in the disabled and non-disabled groups, the bar chart suggests that the disabled group generally has higher mean conflict incidents. This means that the inclination of pedestrians stepping into other's comfort zone happens more frequently among disabled groups than the non-disabled. Other than this, different bus stop types generally influence the mean conflicts of the two groups in the same way, which means that the type leading to higher mean conflict incidents among the pedestrian group also results in the same or similar results among the other group. However, there is one exception – the backing footway in the narrow-high scenario has the least mean conflicts of 10.52 compared to other types in the non-disabled group, but it leads to the meanest conflicts of 29.16 in the disabled group.

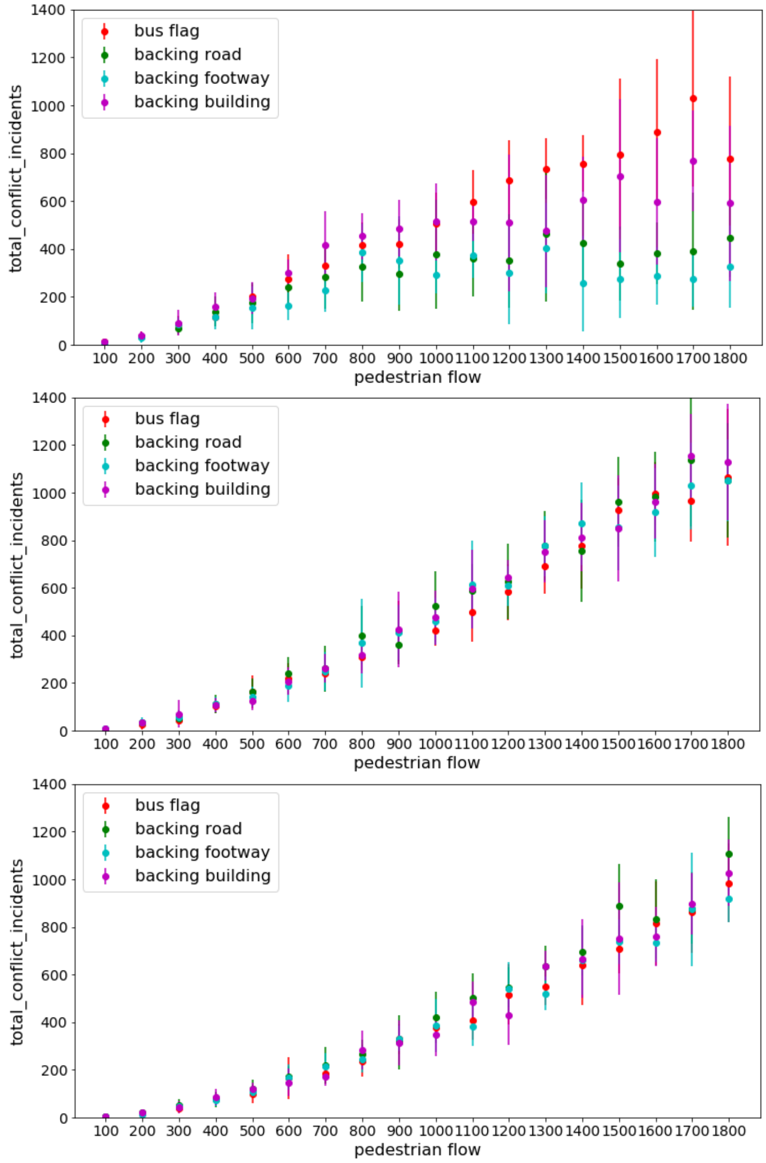

Figure 18 Conflict-flow plots

Indicated by the scatter plots above, the findings on the correlation between total conflict incidents and pedestrian flow are similar to the results of the mean delay time. On medium and wide footways, there is a clear positive correlation relationship between the conflicts and flow, but there is no obvious difference between bus stop types in the sensibility to flow. The amount of conflicts that increase with the flow increase also seems to be very close between these two width conditions. More apparent variances between bus stops exist in the narrow footway situation. On a narrow footway, the bus flag seems to result in a simple linear regression relationship between conflicts and pedestrian flow, while the others do not. For the other three bus stop types, the conflict increases with the flow increase when it is less than around 800 pph. When reaching a medium flow level, the number of conflicts seems to fluctuate around a certain range instead of increase.

5. Discussion

5.1. Results Interpretation

To answer the research question of how different bus stops influence pedestrian movement and experience, the meaning of the results discovered above, in reality, will be interpreted from three aspects. The following three sections will explain how different types of bus stop leads to different movement patterns, sensibility variance to pedestrian flow, and different impacts on disabled and non-disabled pedestrians.

5.1.1. Movement Emergence and Patterns

The performances of bus stops were more differentiated in situations of narrow footway with medium or high pedestrian flow, while in other situations, the final movement patterns and the ways they emerged were similar to each other. On narrow footways with a medium flow, backing footway and backing road bus stops had more similar emergence process and collective features. Compared to the other two types, they had a lower average speed of around 0.26 m/s in the end and reached the final speed faster, which means that the pedestrian flow moved slower on a street with backing road or footway bus stop than with the other types. They also led to a faster increase in density and a larger final pedestrian density, with relatively fewer total incidents of conflict and lower accumulation rates. This suggests that it tended to be more crowded with these two bus stop types, but pedestrians were less inclined to step into others' comfort zone. When there was high pedestrian flow, the bus stop backing road and backing footway still had the same relation to the other two types, but they became differentiated from each other in a way that the backing footway led to a slower average speed, higher pedestrian density, and fewer conflict incidents. Meanwhile, a footway with bus flag was most effective in allowing pedestrians to walk at a faster pace and reduce congestion, but the most likely to cause conflict incidents.

The influence on the density and incidents of conflicts seems to be contradictory, which could possibly be explained by three reasons. First, the congestion occurs when the amount of pedestrian flow exceeds the capacity of the footway, which could lead to fewer conflict incidents with the recording method used in this simulation. Besides reflected through the monitor and space-time plots, the congestion event that happened in the simulation can also be indicated by the density-time plot. When the density keeps increasing at a relatively high rate, it suggests that there is congestion since the number of pedestrians flowing in exceed that of those flowing out. Thus, agents in the narrow-mid and narrow-high scenarios have all experienced congestion.

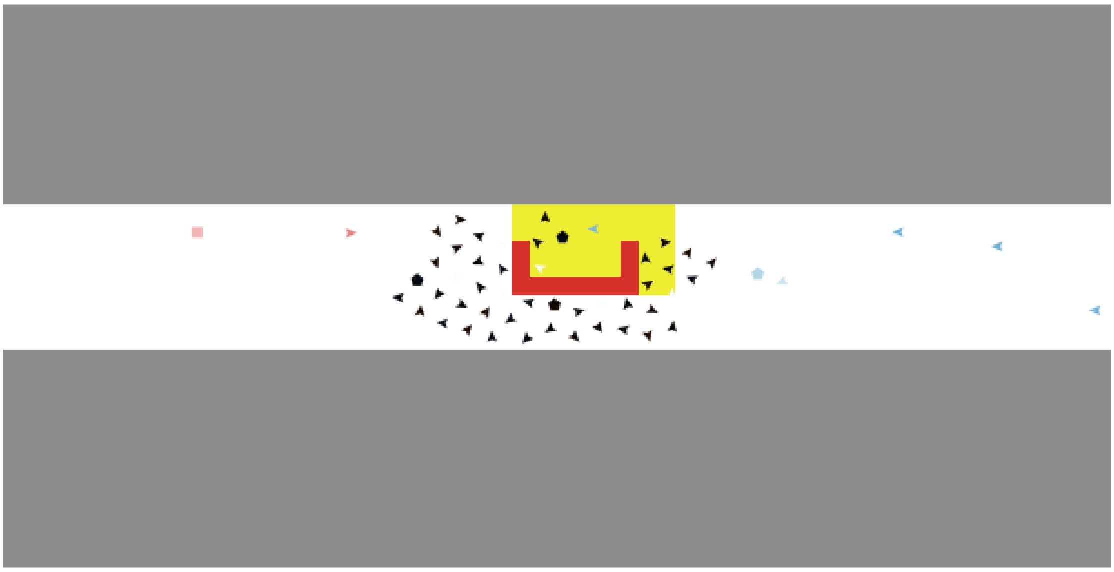

Figure 19 A view of simulation demonstrating congestion event indicated by the black agents around bus stop

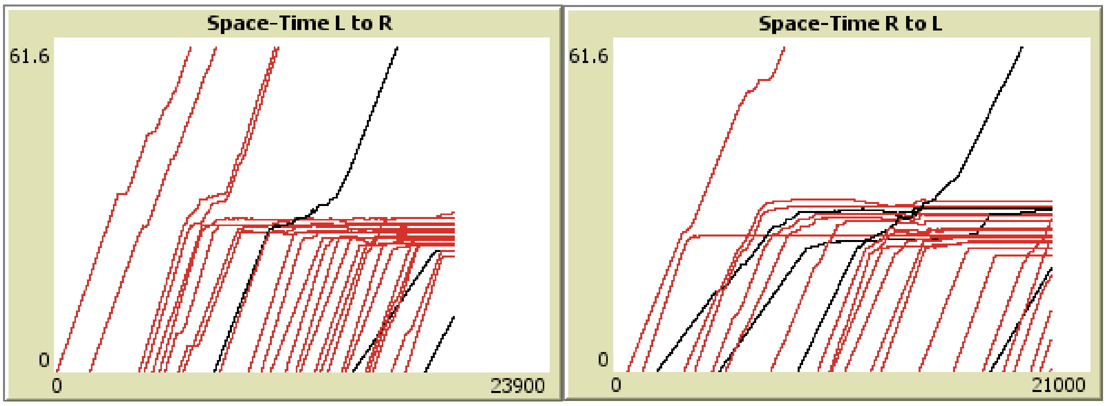

Figure 20 Space-time diagram indicating congestion event with horizontal trajectories, which represents agents not moving forward

However, the recording process of this model lets agents memorise all the different pedestrians who stepped into their comfort zone and will not count the same encountered pedestrian twice. In this case, the conflict incidents of a certain agent will stop accumulating once it is stuck in the congestion since all other agents around it have already been counted, and it has no opportunity to encounter new pedestrians. Therefore, the longer the congestion exists, the slower the conflict incidents accumulate. In other words, this measure is not able to reflect the real experience on conflict incidents when there is congestion, and the small number of the backing footway and backing road in the two scenarios is actually an indication of congestion. Besides, it might also be because pedestrians going for the bus tend to be more concentrated in the waiting area and separated from pedestrians passing by, whose moving trajectories are less impeded. Finally, slower walking speeds also give people more reaction time to avoid being too close to others, thus preventing possible incidents of conflict.

This result suggests that the bus flag type is recommended for the narrow street with medium to high pedestrian flow to allow pedestrians to move through the street more efficiently in a less crowded environment. Meanwhile, in other width-flow combinations, the result of the mean delay time suggests that it would be better to avoid using the backing road bus stop, as it has a greater possibility to take pedestrians longer time to finish the trip. Other than this, the other three types do not make significant differences in all measures when the footway is not narrow or is narrow with low flow.

5.1.2. Sensibility to Pedestrian Flow

As the results demonstrated, the sensibility to pedestrian flow was investigated using the mean delay time and total conflict incidents. The four bus stop types were equally sensitive to the pedestrian flow increase on medium and wide footways, where the mean delay time and total conflict incidents steadily increased with flow increase. However, when the footway was narrow, different bus stops reacted to the flow variation differently. In terms of delay time, the backing footway was the most sensitive while the bus flag was the least sensitive, meaning that a footway with a bus stop that is backing footway could lead to a very different experience on delay time, depending on the amount of pedestrian flow at that moment. However, on the footway with bus flag, a higher pedestrian flow does not necessarily lead to longer delay time.

In terms of conflict incidents, the results are somewhat opposite. When the pedestrian flow is greater than 800 pph, a higher flow results in more conflict incidents on footways with bus flag bus stop, whereas it does not influence the conflict incidents any more on footways with the backing footway bus stop. This could be as a result of how total conflicts are counted, which was discussed in the previous section. Overall, the findings on flow sensibility can be useful when deciding the bus stop type for footways with large variations in pedestrian flow from time to time. On such streets, the street furniture-like bus stop is expected to have enough tolerance to high flow, so that the movement and experience would not be dramatically influenced by the settings. By saying so, the experiment findings here indicate that the bus flag will be a better choice for a narrow footway with a pedestrian flow of large ranges.

4.1.3. Different Impacts on the Disabled and Non-Disabled Pedestrians

The different impacts on the disabled and non-disabled pedestrians are compared to avoid any settings that might not significantly influence one group but have a great negative impact on the other. Thus, in this case, the bus stop that leads to fewer differences in terms of the mean delay time and total conflict incidents between pedestrian groups is preferred. The results have demonstrated that streets with backing footway or backing road bus stops have a greater possibility to bring different experiences. This refers to the delay time and conflicts, and the two groups of pedestrians, especially in the situations of the narrow street with medium to high flow. So, to balance the experiences of the different groups, the bus flag or backing building bus stop will be more effective choices.

5.2. Limitations

Due to various sources of errors and processes involving approximation, some of the findings may not be accurate enough in reflecting reality. To clarify to what degree the model and analysis can answer the research question, this section will discuss the limitations of the research from three perspectives: model construction, experiment settings and analysis methods.

One of the major limitations lies in the model constructed, which has a limited capacity to replicate real human walking behaviour. First, the core mechanism of the SFM used to drive the walking behaviour has its drawbacks. As previously stated in the literature review, SFM could lead to unrealistic movements such as trajectory oscillation, which can be observed in the space-time diagram when the simulation is running. The simple interpretation of the movement motivation to forces ignores the more complex processes of environmental perception and negotiations between pedestrians. Thus, behaviours like avoiding the bus in advance due to knowledge of the existence of the bus stop from a relatively long distance away, or stopping and waiting for others to pass first, were not able to be simulated in this model.

Other than this, the additional processes designed for pedestrians to avoid the bus stop have the issue of oversimplification. To avoid the bus stop being an obstacle, the behaviour defining model simply directed agents in a distance of two metres and walked towards the bus stop to the corner closest to the central line of the footway. In this way, all the pedestrians needed to pass by the bus stop and behave in a way that the bus stop is not noticeable until within two metres from it, and passing that inner corner is the only route to avoid the bus stop. People may perceive that and start to avoid obstacles at different time steps and bypass them using different routes. This simplified interpretation of the avoiding behaviour is effective in preventing agents from being stuck by the bus stop in this model. However, it does not reflect the real avoidance process. Similar issues exist in the process of approaching the waiting area and adjusting to the preferred waiting position, which is selected randomly, whereas people may have certain preference and considerations instead of standing, which may be inside or outside the shelter.

Therefore, some of the pedestrian interactions may be unrealistic and lead to inaccurate statistics used to evaluate the impact of bus stops, so that some findings of their influences could be misinterpreted.

The way the environment was built in the simulation also led to the inaccuracy of the results due to the simplification of the street settings, abstract of the bus stop shape, the approximation of the bus stop dimensions, and the shape of the waiting area. The simulated environment excluded all other street furniture in the model to better control the variables that could influence pedestrian movement. However, pedestrian movement is a complex system in which human behaviours are shaped by various intertwined internal and external elements, so the existence of one setting may influence the performance of another. So, in some circumstances, when there are other influential variables, the impact of the bus stop type could either be weakened or enhanced. Thus, the impact of bus stops should be discussed in a specific context to the meaning in reality.

In terms of the shape abstract and dimension approximation of the bus stops, the model shaped the bus stops with approximated shapes and dimensions to fit the raster-based simulation environment. Such an arrangement might have changed the actual shape of the available space for agents to move around, so, that influenced the way in which pedestrians interacted with the environment. In addition to the shape of the bus stops, the shape of waiting area, which was set to be a rectangle around the bus stop, could also be more flexible since people will not exactly be restricted to a rectangular area while waiting for the bus in reality. All the above variance in simulated behaviours from real-world behaviours has the possibility of leading to inaccurate collective movement features and then, being misinterpreted as the influences from bus stops.

The second limitation falls in the simulation settings, particularly referring to the pedestrian input data. The statistics on walking behaviour, including desired walking speed and spacing, were taken from the previous pedestrian laboratory experiment in a controlled environment. However, people may have different speed and spacing when walking in indoor and outdoor environments. Thus, there may be a variance between the statistics used and its characteristics when people walk on real streets with those settings. Besides, the mass and size of pedestrians were approximated, and lack of variation also did not reflect the real situation. Besides the limitation on input data, the way to calculate the output as a measurement of the movement has also led to the inadequacy of the results. As discussed in the result interpretation section, the way to count the total conflict incidents has resulted in seemingly contradictory patterns. Thus, a better approach to measure the movement quality is needed to reflect the impact of bus stops more accurately. The last limitation is about the analysis process. The current analysis mostly depends on basic statistical summaries on the experiment outputs. The findings were also described based on the estimation of the relationship. In particular, the analysis on the pedestrian flow sensibility was aimed to investigate the relationship between a collective feature with the flow, which should have been suitable for regression analysis, so that the relationship could be quantitatively represented. However, due to the limited sample size, the result of the regression would not be convincing. Therefore, the analysis only involved basic qualitative descriptions based on the diagrams produced, which tends to be superficial.

6. Conclusion

To conclude the paper, the research question, 'how different bus stop types influence the pedestrian movement and experience differently', can be answered based on the investigation with an agent-based model grounded in the algorithm of Social Force Model. Overall, the four selected bus stop types are more differentiated on their impacts on pedestrian movement in the situation of a narrow street with medium or high pedestrian flow. In such a situation, the bus flag tends to be more capable of letting pedestrians move faster in a less crowded environment and is less sensitive to the pedestrian flow increase, while the backing footway does the opposite. This is not surprising as it takes the least room; thus, there is space for pedestrians to move about freely, while the backing footway bus stop somehow creates a bottleneck-like situation on a narrow footway. Besides, the bus flag and backing building are less likely to create very different experiences in delay time and conflict incidents between disabled and non-disabled individuals. These findings confirm the possibility of applying such simulation in street design decisions.

However, these findings might not be able to fully and accurately answer the research question due to the various limitations that were present throughout the simulation and analysis process. According to the limitations discussed before, this research can be improved and extended in various ways to more comprehensively and precisely explain the impact of bus stop types on pedestrian flow. To make the simulated walking behaviour more realistic, better avoidance algorithm is needed. Finer and more complex environmental settings will also help to build a more realistic simulation world. It is also necessary to validate and calibrate the model with real-world trajectory data. In terms of improvement in analysis methodologies, sensibility test with smaller flow intervals is expected to produce more informative results with a deeper analysis that can reveal the relationship between variables in more details. Other than this, the research can also be expanded with future works on investigating the impact of other street settings, testing the sensibility of different proportions of disabled individuals, involving more variables to represent the movement quality, and so on.

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Appendix

Netlogo code of the model and simulation

```
globals [
  lower-edge
  upper-edge
  bus-frequency

  ped-waiting
  delay-record
  delay-record-dis
  delay-record-non
  collision-count
  colli-count-dis
  colli-count-non
]
patches-own [
  waiting-area?
  possible-pp
]
turtles-own[
  ;; personal traits
  desire-speed
  relaxation-t
  sense-radius
  body-radius
  mass
  comfort-radius
  ability
  ;; movement releated
  desire-v-x
  desire-v-y
  moment-speed-x
  moment-speed-y
  moment-speed
  d-wall
  total-force
  collision
  start-end
  delay
  start-tick
  for-bus?
  behavior
  destination
  preferred-p
```

```
]

to setup

  ca
  reset-ticks

  setup-world
  setup-bus-stop

  set delay-record []
  set delay-record-dis []
  set delay-record-non []
  set collision-count []
  set colli-count-dis []
  set colli-count-non []

end

to setup-world

  ;; setup the sidewalk with white patches
  set lower-edge (31 - sidewalk-width * 2) / 2
  set upper-edge lower-edge + sidewalk-width * 2
  ask patches with [pycor < upper-edge and pycor > lower-edge] [set pcolor white]
  ask patches with [pycor > upper-edge or pycor < lower-edge] [set pcolor grey]
  set bus-frequency 1

end

to setup-bus-stop

  ;; setup the bus stop based on type choice
  ;; then define the avoid area and waiting area based on bus stop type

  ;; bus flag
  if bus-stop-type = "bus flag" [
    ask patches with [pxcor >= 33 and pxcor <= 39 and (pycor < upper-edge and
pycor > upper-edge - 4)] [set waiting-area? 1 set pcolor yellow]
    ask patches with [pycor = (upper-edge - 1.5) and pxcor = 34] [
      set pcolor red
      set waiting-area? 0
    ]
  ]

  ;; backing road
  if bus-stop-type = "backing road" [
```

```
    ask patches with [pycor < upper-edge - 1 and pycor >= upper-edge - 5.5 and pxcor
< 37 and pxcor > 27] [set waiting-area? 1 set pcolor yellow]
    ask patches with [(pycor = (upper-edge - 1.5) and pxcor > 27 and pxcor < 35) or
(pxcor = 28 or pxcor = 34 and (pycor = (upper-edge - 2.5) or pycor = (upper-edge -
3.5)))] [
      set pcolor red
      set waiting-area? 0
    ]
  ]

  ;; backing footway
  if bus-stop-type = "backing footway" [
    ask patches with [pycor < upper-edge and pycor >= upper-edge - 4.5 and pxcor <
37 and pxcor > 27] [set waiting-area? 1 set pcolor yellow]
    ask patches with [(pycor = (upper-edge - 4.5) and pxcor > 27 and pxcor < 35) or
(pxcor = 28 or pxcor = 34 and (pycor = (upper-edge - 3.5) or pycor = (upper-edge -
2.5)))] [
      set pcolor red
      set waiting-area? 0
    ]
  ]

  ;; backing building
  if bus-stop-type = "backing building" [
    ask patches with [pycor > lower-edge and pycor <= lower-edge + 4.5 and pxcor <
37 and pxcor > 27] [set waiting-area? 1 set pcolor yellow]
    ask patches with [(pycor = (lower-edge + 0.5) and pxcor > 27 and pxcor < 35) or
(pxcor = 28 or pxcor = 34 and (pycor = (lower-edge + 1.5) or pycor = (lower-edge +
2.5)))] [
      set pcolor red
      set waiting-area? 0
    ]
  ]

end

to set-ped
  ;; pedestrian initialization

  let a random-float 1
  if a <= disabled-proportion [set-visually-impaired]
  if a > disabled-proportion and a <= disabled-proportion * 2 [set-non-motorized]
  if a > disabled-proportion * 2 and a <= disabled-proportion * 3 [set-motorized]
  if a > disabled-proportion * 3 [set-non-disabled]

  set relaxation-t 0.5
  set moment-speed-y 0
```

```
  ifelse xcor = 0
  [set start-end 0 set heading 90 set moment-speed-x desire-speed set color (62 - 10
* moment-speed-x) / 3]
  [set start-end 60 set heading -90 set moment-speed-x 0 - desire-speed set color
(274 - 10 * moment-speed-x) / 3]
  ifelse random-float 1 < 0.1 [set for-bus? 1] [set for-bus? 0]

  set collision []
  set start-tick ticks

end

to set-visually-impaired

  set ability "visually-impaired"
  set shape "circle"
  set size 0.75
  set sense-radius 0.4
  set body-radius 0.25
  set mass 65
  set comfort-radius random-normal-in-bounds 1.39 0.43 0.96 1.82
  set desire-speed random-normal-in-bounds 0.97 0.23 0.74 1.2

end

to set-non-motorized

  set ability "non-motorized"
  set shape "pentagon"
  set size 0.75
  set sense-radius 0.7
  set body-radius 0.4
  set mass 100
  set comfort-radius random-normal-in-bounds 1.68 0.31 1.37 1.99
  set desire-speed random-normal-in-bounds 0.68 0.17 0.51 0.85

end

to set-motorized

  set ability "motorized"
  set shape "square"
  set size 0.75
  set sense-radius 0.7
  set body-radius 0.4
  set mass 100
  set comfort-radius random-normal-in-bounds 1.73 0.37 1.36 2.1
```

```
  set desire-speed random-normal-in-bounds 0.78 0.21 0.57 0.99

end

to set-non-disabled

  set ability "non-disabled"
  set size 0.75
  set sense-radius 0.7
  set body-radius 0.25
  set mass 65
  set comfort-radius random-normal-in-bounds 1.52 0.4 1.12 1.92
  set desire-speed random-normal-in-bounds 1.12 0.16 0.96 1.28

end

to-report random-normal-in-bounds [m std l u]

  let a random-normal m std
  if a > u or a < l [report random-normal-in-bounds m std l u]
  report a

end

;; ------------------------------------------------------------------------

to go

  ; make movement
  sprawn-ped
  define-behavior
  calc-total-force
  move

  ; record measurements
  record-collision
  experience

  ; plot space-time
  plotter-LR
  plotter-RL

  ; update color and heading
  updates

  ; turtles finished trip die
  leave
```

```
  tick

end

;;---------------------------------------------------------------------

to sprawn-ped

  let inflow pedestrian-flow / 3600 * 0.005 * 2
  if random-float 1 < inflow [
    set ped-waiting ped-waiting + 1
    if ped-waiting > 0 [
      crt 1 [
        set xcor one-of [0 60]
        set ycor (lower-edge + 1) + random-float (sidewalk-width * 2 - 2)
        set-ped
        if any? other turtles in-radius (comfort-radius * 2) [die]
      ]
        set ped-waiting ped-waiting - 1
    ]
  ]

end

to define-behavior

  ;; set the behavior mode for turtles based on their current position and final
destination (for-bus?)
  ask turtles [
    ifelse for-bus? = 0 [
      let w min [pxcor] of patches with [pcolor = red]
      let ea max [pxcor] of patches with [pcolor = red]
      let n max [pycor] of patches with [pcolor = red]
      let s min [pycor] of patches with [pcolor = red]
      ifelse (start-end = 0 and xcor >= w - 4.5 and xcor < w - 0.5 and ycor <= n + 1 and
ycor >= s - 1) or (start-end = 60 and xcor <= ea + 4.5 and xcor > ea + 0.5 and ycor <= n
+ 1 and ycor >= s - 1) [
        set behavior "bypassing"
      ] [set behavior "passing"]
    ] [
      ifelse [waiting-area?] of patch-here = 1 [
        assign-pp
        ifelse round xcor = first preferred-p and round ycor = last preferred-p [
          if behavior != "boarding" [set behavior "waiting"]
        ] [
          if behavior != "boarding" [set behavior "adjusting"]
```

```
      ]
    ] [
      if behavior != "boarding" [set behavior "approaching"]
    ]
   ]
  ]

  if remainder ticks bus-frequency * 12000 = 6000 [
   let waiting-peds turtles with [behavior = "waiting" or behavior = "adjusting"]
   let waiting-num count waiting-peds
   let boarding-num random waiting-num
   ask n-of boarding-num waiting-peds [set behavior "boarding"]
  ]

end

to assign-pp

  ;; assign a preperred position for for-bus pedestrians arriving the waiting area
  ifelse preferred-p = 0 [
   set possible-pp one-of patches with [pcolor = yellow and any? turtles-here = false]
   let pp-x [pxcor] of possible-pp
   let pp-y [pycor] of possible-pp
   set preferred-p list pp-x pp-y
  ] [
   set preferred-p preferred-p
  ]

end

;; create reporter for x and y components of three forces
;; 1. will force
to-report will-force

  ;; determine intermediate destination and calculate current desire velocity based
on bahavior mode
  set-destination
  calc-desire-v

  ;; report a list of x and y components of the speed caused by will force
  let x-will (desire-v-x - moment-speed-x) * mass / relaxation-t
  let y-will (desire-v-y - moment-speed-y) * mass / relaxation-t
  report list x-will y-will

end

to set-destination
```

```
 ;; set the current destination point
 ask turtles with [behavior = "passing"] [
  ifelse start-end = 0 [set destination list 61 ycor] [set destination list -1 ycor]
 ]

 ask turtles with [behavior = "bypassing"] [
  ifelse bus-stop-type != "backing building" [
   let dest-y min [pycor] of patches with [pcolor = red] - 1
   let reference min-one-of patches with [pcolor = red] [distance myself]
   let dest-x [pxcor] of reference
   set destination list dest-x dest-y
  ] [
   let dest-y max [pycor] of patches with [pcolor = red] + 1
   let reference min-one-of patches with [pcolor = red] [distance myself]
   let dest-x [pxcor] of reference
   set destination list dest-x dest-y
  ]
 ]

 ask turtles with [behavior = "approaching"] [
  let possible-dest patches with [waiting-area? = 1]
  let dest-p min-one-of possible-dest [distance myself]
  let dest-x [pxcor] of dest-p
  let dest-y [pycor] of dest-p
  set destination list dest-x dest-y
 ]

 ask turtles with [behavior = "adjusting"] [
  set destination preferred-p
 ]

 ask turtles with [behavior = "waiting"] [
  set destination list xcor ycor
 ]

 ask turtles with [behavior = "boarding"] [
  ifelse bus-stop-type = "backing road" and xcor < 34 [
   set destination list 34 (upper-edge - 4.5)
  ] [
   set destination list 35 upper-edge
  ]
 ]

end

to calc-desire-v
```

```
  ;; calculate desired velocity (i.e. set desire-v-x and desire-v-y)
  ask turtles with [behavior = "waiting"] [set desire-v-x 0 set desire-v-y 0]

  ask turtles with [behavior = "adjusting"] [
    let wait-d 4 * desire-speed * 0.5 / mass
    let d-dest sqrt ((first destination - xcor) ^ 2 + (last destination - ycor) ^ 2)
    ifelse d-dest <= wait-d [
      set desire-v-x desire-speed * d-dest / wait-d * (first destination - xcor) / d-dest
      set desire-v-y desire-speed * d-dest / wait-d * (last destination - ycor) / d-dest
    ] [
      set desire-v-x desire-speed * (first destination - xcor) / d-dest
      set desire-v-y desire-speed * (last destination - ycor) / d-dest
    ]
  ]

  ask turtles with [behavior != "waiting" and behavior != "adjusting"] [
    let d-dest sqrt ((first destination - xcor) ^ 2 + (last destination - ycor) ^ 2)
    set desire-v-x desire-speed * (first destination - xcor) / d-dest
    set desire-v-y desire-speed * (last destination - ycor) / d-dest
  ]

end

;; 2. wall force

to-report wall-force [turtle-i]

  ;; check the distance from the two boudaries, report a list of x and y components of
wall force
  ;; upper wall opens for boarding group
  let r [body-radius] of turtle-i
  let y [ycor] of turtle-i
  let d (min list abs (upper-edge - y) abs (lower-edge - y)) / 2
  ifelse y < 15.5 [set d-wall d] [set d-wall (0 - d)]

  ifelse d <= sense-radius [
    let x [xcor] of turtle-i
    ifelse [behavior] of turtle-i = "boarding" and x >= 33.5 and x <= 36.5 [report list 0 0]
[
      if d >= r [
      let y-force 2000 * exp ((r - d) / 0.08) * d-wall / d
      report list 0 y-force
      ]
    if d < r [
      let y-force (2000 * exp ((r - d) / 0.08) + 24000 * (r - d)) * d-wall / d
      let x-force 0 - (r - d) * moment-speed-x
```

```
    report list x-force y-force
    ]
   ]
  ] [ report list 0 0 ]

end

;; 3. interaction force

to-report ped-force [turtle-i turtle-j]

  ;; report a list of x and y components of all the interactive forces caused by one
other pedestrian in the sense radius

  let r-i [body-radius] of turtle-i
  let r-j [body-radius] of turtle-j
  let d-ij [distance turtle-j] of turtle-i
  let x-i [xcor] of turtle-i
  let y-i [ycor] of turtle-i
  let x-j [xcor] of turtle-j
  let y-j [ycor] of turtle-j
  let x-v-i [moment-speed-x] of turtle-i
  let y-v-i [moment-speed-y] of turtle-i
  let x-v-j [moment-speed-x] of turtle-j
  let y-v-j [moment-speed-y] of turtle-j

  let g r-i + r-j - d-ij / 2
  if g <= 0 [set g 0]
  let x-c (x-i - x-j) / d-ij
  let y-c (y-i - y-j) / d-ij

  let x-avoid (2000 * exp (g / 0.08) + 24000 * g) * x-c
  let y-avoid (2000 * exp (g / 0.08) + 24000 * g) * y-c
  let x-fric g * ((y-v-i - y-v-j) * x-c * y-c - (x-v-i - x-v-j) * (y-c ^ 2))
  let y-fric g * ((x-v-i - x-v-j) * x-c * y-c - (y-v-i - y-v-j) * (x-c ^ 2))

  report list (x-avoid + x-fric) (y-avoid + y-fric)

end

to-report ped-force-total [turtle-i]

  ;; report a list of total pedestrian forces from all interacting turtles on a turtle in
both directions
  ;; way to add on interaction forces varied for different groups
  let inter-ped [other turtles in-cone (sense-radius * 2) 180] of turtle-i
  ifelse any? inter-ped [
```

```
    let p-x 0
    let p-y 0
    foreach [who] of inter-ped [x ->
      let ped-force-j ped-force turtle-i turtle x
      set p-x p-x + first ped-force-j
      set p-y p-y + last ped-force-j
    ]
    report list p-x p-y
  ] [report list 0 0]

end

to-report bus-stop-force [turtle-i]

  ;; calculate the avoidance force from the bus stop
  let inter-patches [patches with [pcolor = red] in-radius 1] of turtle-i
  ifelse any? inter-patches [
    let p-x 0
    let p-y 0
    ask inter-patches [
      let r-i [body-radius] of turtle-i
      let d-i distance turtle-i
      let x-i [xcor] of turtle-i
      let y-i [ycor] of turtle-i
      let x-v [moment-speed-x] of turtle-i
      let y-v [moment-speed-y] of turtle-i

      let g r-i + 0.25 - d-i / 2
      if g <= 0 [set g 0]
      let x-c (x-i - pxcor) / d-i
      let y-c (y-i - pycor) / d-i

      let x-avoid (2000 * exp (g / 0.08) + 24000 * g) * x-c
      let y-avoid (2000 * exp (g / 0.08) + 24000 * g) * y-c
      let x-fric g * (y-v * x-c * y-c - x-v * (y-c ^ 2))
      let y-fric g * (x-v * x-c * y-c - y-v * (x-c ^ 2))

      set p-x x-avoid + x-fric
      set p-y y-avoid + y-fric
    ]
    report list p-x p-y
  ] [report list 0 0]

end

to-report interaction-force [turtle-i]
```

```
  let i-x first ped-force-total turtle-i + first bus-stop-force turtle-i
  let i-y last ped-force-total turtle-i + last bus-stop-force turtle-i
  report list i-x i-y

end

;; calculate the total social force on each turtle
to calc-total-force

  ask turtles [
    let will will-force
    let wall wall-force self
    let inter interaction-force self
    let f-x first will + first wall + first inter
    let f-y last will + last wall + last inter
    set total-force list f-x f-y
  ]

end

;; -------------------------------------------------------------------------------------------

;; calculate the speed change and position change and move turtle to the new
position
to-report dv [force v-start]
  ;; given the list of total force, and the list of speed change in both directions
  ;; report a list of speed change in x and y direction
  let d-x 0.005 / mass * first force
  let d-y 0.005 / mass * last force

  report list d-x d-y

end

to-report position-change [v-start v-change]
  ;; given the start speed and speed change in both directions
  ;; report a list of distance change in x and y direction
  let d-x (first v-start + 0.5 * first v-change) * 0.005 * 2
  let d-y (last v-start + 0.5 * last v-change) * 0.005 * 2
  report list d-x d-y

end

to move

  ;; make movement
  ask turtles [
```

```
    let v-start list moment-speed-x moment-speed-y
    let v-change dv total-force v-start
    set xcor xcor + first position-change v-start v-change
    set ycor ycor + last position-change v-start v-change
    set moment-speed-x moment-speed-x + first v-change
    set moment-speed-y moment-speed-y + last v-change
    ifelse moment-speed-x != 0 [
      set heading atan moment-speed-x moment-speed-y
    ] [
      if moment-speed-y > 0 [set heading 0]
      if moment-speed-y < 0 [set heading 180]
    ]
  ]

end

;;-----------------------------------------------------------------------------------------

to record-collision

  ;; record collision
  ask turtles [
    if behavior = "passing" or behavior = "bypassing" or behavior = "approaching" [
      let current-colli other turtles in-cone (comfort-radius * 2) 180
      if any? current-colli [
        foreach [who] of current-colli [ x ->
          if not member? x collision [set collision lput x collision]
        ]
      ]
    ]
  ]

end

to experience

  ;; record delay and collision incidents for turtles about to finish the trip
  let finish turtles with [abs (xcor - start-end) >= 60]
  if any? finish [
    ask finish [
      ;; record actual time used to go through the channel
      set delay (ticks - start-tick) * 0.005 - 30 / desire-speed
      set delay-record lput delay delay-record

      ;; record times the turtles get too close to others
      set collision-count lput length collision collision-count
```

```
      ;; record the delay time and collision count for disabled/non-disabled groups
respectively
      ifelse ability != "non-disabled" [
        set delay-record-dis lput delay delay-record-dis
        set colli-count-dis lput length collision colli-count-dis
      ] [
        set delay-record-non lput delay delay-record-non
        set colli-count-non lput length collision colli-count-non
      ]
    ]
  ]

end

to-report total-colli

  ifelse empty? collision-count = false [report sum collision-count] [report 0]

end

to-report mean-colli-dis

  ifelse empty? colli-count-dis = false [report sum colli-count-dis / length colli-count-
dis] [report 0]

end

to-report mean-colli-non

  ifelse empty? colli-count-non = false [report sum colli-count-non / length colli-
count-non] [report 0]

end

to-report mean-delay

  ifelse empty? delay-record = false [
    report sum delay-record / length delay-record
  ] [report 0]

end

to-report mean-delay-dis

  ifelse empty? delay-record-dis = false [
    report sum delay-record-dis / length delay-record-dis
  ] [report 0]
```

```
end

to-report mean-delay-non

  ifelse empty? delay-record-non = false [
    report sum delay-record-non / length delay-record-non
  ] [report 0]

end

to updates

  ask turtles [
    set moment-speed sqrt (moment-speed-x ^ 2 + moment-speed-y ^ 2)
    ifelse heading > 0 and heading <= 180
    [set color (62 - 10 * moment-speed) / 3]
    [set color (302 - 10 * moment-speed) / 3]
  ]

end

to leave

  ;; remove pedestrians reaching the boundaries
  ask turtles with [ xcor < 0 or xcor > 60 or ycor >= upper-edge] [die]

end

;; plot space time diagram
to plotter-LR

  set-current-plot "Space-Time L to R"
  let passersby turtles with [(behavior = "passing" or behavior = "bypassing") and
start-end = 0]
  if any? passersby
  [
    ask passersby
    [
      create-temporary-plot-pen word (who) ("")
      ifelse ability = "non-disabled" [set-plot-pen-color red] [set-plot-pen-color black]
      plotxy ticks xcor
    ]
  ]

end
```

```
to plotter-RL

  set-current-plot "Space-Time R to L"
  let passersby turtles with [(behavior = "passing" or behavior = "bypassing") and
start-end = 60]
  if any? passersby
  [
    ask passersby
    [
      create-temporary-plot-pen word (who) ("")
      ifelse ability = "non-disabled" [set-plot-pen-color red] [set-plot-pen-color black]
      plotxy ticks (60 - xcor)
    ]
  ]

end


;; reporters used in BehaviorSpace
to-report speed-reporter

  ifelse empty? [moment-speed] of turtles = false [report mean [moment-speed] of
turtles] [report 0]

end
```