Analysis on Alighting and Boarding Movement Laws in Subway Using Modified Social Force Model

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Abstract **-** This paper presents a multi-agent simulator based on social force model to simulate each passenger's boarding and alighting behavior both in a train and on a platform seamlessly. Passengers can be divided into three types: to board, alight and stay in train. They have different individual attributes and follow different walking rules. Due to the characteristics of subway environment and passengers' behavior in boarding and alighting, some adjustment and improvement were made to the basic social force model: (1) In some cases during the process of boarding and alighting, the driving force targeting to destination needs to be doubled, and the repulsion force between two agents needs to be reduced. (2) Passengers who stay in the train show quite different movement from the usual pedestrian. They usually want to remain still, unless they are in front of the door. To describe their behaviors, we introduced a tangent detour force. The scope of the interaction between agents is extended and some passengers out of the visual field also should be counted. (3) Divide the repulsive force between an agent and an obstacle into the frontal force and convex corner force. These two forces have different spheres of influence and calculation methods. The agents could exhibit reasonable intelligence and diversity during alighting and boarding.

Keywords**:** multi agent; micro-simulation; alighting and boarding movement; subway station; social force model

1. Introduction

Passengers' boarding and alighting is an inevitable event in a subway system. With the short departure interval of trains (less than 2 minutes in some lines), limited dwell time and large passenger flow, a well-ordered organization of boarding and alighting is essential to guarantee the trains' departure without delay.

The existing research mainly focused on the survey and statistics of time [1-4], but did not cover the influencing factors and mechanisms of boarding and alighting. In addition, there is insufficient attention to modeling the process of alighting and boarding. [5] modeled this process by Cellular Automata Model, but the passengers who stay in the car were not taken into consideration. And due to the mesh generation of the CA model, the passengers' walking path is very mechanical, which was far from the actual situation. [6, 7] did similar work by the Potential Model, but failed to fully describe the behavior characteristics of different passengers.

To solve these problems, this paper presents a multi-agent simulator based on social force model to simulate each passenger's boarding and alighting behavior both in a train and on a platform seamlessly. Passengers can be divided into three types: to board, alight and stay in train. They have different individual attributes and follow different walking rules. The agents could exhibit reasonable intelligence and diversity during alighting and boarding.

2. Model

2.1 Passenger behaviour during alighting and boarding

There are three components of passengers in the model: the alighting passenger moving from the car to the platform, the boarding passenger moving from the platform to the car through the doors, and the staying on-board passengers (through-standees).

The whole process of alighting and boarding can be divided into four stages.

Stage Ⅰ: Before a train arrives at a station. The alighting passengers queue up beside the door at the platform, and the passengers get ready to get off and move towards the door.

Stage Ⅱ: A train arrives at the station and the door opens, alighting passengers start to get off while boarding passengers wait in queue beside the door. This stage will last until the last alighting passengers get out of the train.

Stage Ⅲ: The boarding passengers start to get on.

Stage Ⅳ: The door closes and the train runs to the next station. The boarding passengers and the through-standees may adjust their positions in the train slightly for comfort. Then, they will go into a balanced state.

It is also a common phenomenon that the boarding passengers crowd around the door, hurrying to board, and hamper alighting ones. So, stage 2 and 3 may have some overlap, or even run simultaneously.

2.2 Social force model

According to the social force model (SFM), the system is updated at every time step and each of the passengers in simulation system can move to a new position at each discrete time step t → t+1 according to a driving force. In the following, we describe a social force model for pedestrian motion dynamics by considering personal motivations and environmental constraints.

2.2.1. Desired Force

Desired force reflects the desire of a passenger to move to a target. It can be defined as Equation 1.

$$\vec{F}_{i,t}^{seek} = m_i \frac{1}{\tau}\left(v_i^0 \vec{e}_{i,t} - \vec{v}_{i,t}\right) \tag{1}$$

where $\vec{F}_{i,t}^{seek}$ the desired force of agent i at time t, m_i is the mass, v_i^0 is the velocity that the pedestrian i wants to achieve, $\vec{e}_{i,t}$ is the normalized vector pointing to the direction where the pedestrian i wants to go, $\vec{v}_{i,t}$ is the pedestrian current velocity, and τ is the time relaxing constant.

The boarding passengers would be driven by this force only in stage Ⅲ; the alighting passengers would be driven from stage Ⅱ, until they leave the platform. It is assumed that the through-standees are not driven by a desired force in the train. But one case is exceptional. If a through-standee was located near the door, he would be greatly disturbed by the alighting and boarding passengers. Therefore, for comfort, he would take the initiative to change his position so that other passengers can get on and off smoothly. Therefore, a restricted zone is set up in front of each door inside the train. The through-standees would be driven by a desired force when they enter the restricted zones.

In case of huge amount of passengers, it may be difficult to get off/on and sometimes passengers need to surge forward to achieve their goals. To reflect their strong wishes to get off/on, the desired force should be modified as equation 2 in the following two cases: (1) the desired force of an alighting passenger should be doubled from Stage Ⅱ until he goes out of the car and leaves the door with a distance of 0.5m. The distance of 0.5m is taken because of the gap between the train and the platform, and the passenger's body size. (2) The desired force of a boarding passenger should be doubled when he is near the door, that is, in a range of 0.5 m outside the door and 0.125 m inside the door.

$$\overrightarrow{F'}_{i,t}^{seek} = 2 * \vec{F}_{i,t}^{seek} \tag{2}$$

2.2.2. Social Force

In SFM, the exclusive force between pedestrians, $\overrightarrow{F_{i,t}^{\text{social}}}$, is expressed as a net force of the psychological exclusive force, $\vec{F}_{i,j,t}^{\text{social repulsive}}$, the physical extrusion pressure, $\vec{F}_{i,j,t}^{\text{pushing}}$, and the friction force, $\vec{\mathrm{F}}_{i,j,t}^{\text{friction}}$, as shown in equation 3. The latter two exist only when pedestrians i and j have physical contact. The psychological repulsion is modified with density and direction, as shown in equation 4 and 5.

$$\vec{\mathrm{F}}_{i,t}^{\text{social}} = f_{density,i} * \sum f_{direction,i,j} * \vec{\mathrm{F}}_{i,j,t}^{\text{social repulsive}} + \sum \vec{\mathrm{F}}_{i,j,t}^{\text{pushing}} + v_{ij,t}^{\tau} \sum \vec{\mathrm{F}}_{i,j,t}^{\text{friction}} \tag{3}$$

$$f_{density,i} = 0.3\left(1 - D_{i,t}\right) \tag{4}$$

$$f_{direction,i,j} = \lambda + 0.5(1-\lambda)\left(1 + \cos\alpha_{t,i,j}\right) \tag{5}$$

where $f_{density,i}$ and $f_{direction,i,j}$ are the correction factor of density and direction, $v_{ij,t}^{\tau}$ is the relative velocity in tangent direction of passengers *i* and *j*, λ is direction weight, $\alpha_{t,i,j}$ is the angle between the current position of passengers i, j and the current target point of pedestrian *i*. $D_{i,t}$ is the utilization of space around pedestrian i, $D_{i,t} = \sum_{k=1}^{N_{i,t}} A_k / A_i^{visual}$, it is the ratio of total area of passenger in the vision field and the area of vision field (A_i^{visual}), $D_{i,t} \le 1$。The number of passengers in the vision field is $N_{i,t}$ and the horizontal projection area of pedestrian *k* is A_k。

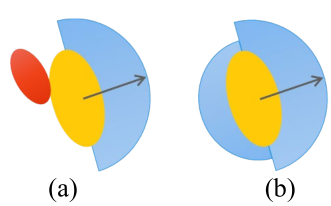
The alighting passenger needs to cross through the waiting boarding passengers, who are lined up on both sides of the door. There is a narrow space left for alighting passengers, so they have less psychological exclusion with the queued boarding passengers. The waiting passengers on both sides can be regarded as a virtual wall and the psychological exclusive force between an alighting passenger i and a boarding passenger in queue j could be set as zero in the direction parallel to the train. In the direction perpendicular to the train, the psychological exclusive force should be halved, as shown in equation 6.

$$\begin{aligned} \mathrm{F'}_{y,i,j,t}^{\text{social repulsive}} &= 0 \\ \mathrm{F'}_{x,i,j,t}^{\text{social repulsive}} &= \mathrm{F}_{x,i,j,t}^{\text{social repulsive}}/2 \end{aligned} \tag{6}$$

The carriage is always crowded, moving slowly, and it is normal to make physical contact with other passengers. So passengers have reduced expectation of personal space. The social force works in a much smaller scope, with the view angle of 180 degree and the radius of 0.5m, as the blue region in Figure 1a.

In addition to the passengers in the vision field, other passengers (the red agent in Figure 1a) who have physical contact with passenger i also make a social force, though they are out of the vision field.

Sometimes, a through-standee may get in the way of an alighting/boarding passenger behind him. In real life, the alighting/boarding passenger would remind the through-standee by physical contact or verbal communication. In order to solve this dilemma, the range of social force for a through-standee is expanded to 0.3 m behind him, as shown in Figure 1b.



(a) (b)

Fig. 1: The scope where social force worked

2.2.3. Centripetal Force

Deadlock occurs when a through-standee and an alighting passenger are in some special relative position. To solve this problem, the centripetal force (equation 7) is introduced in this paper.

Agent i (the red one in Fig. 2) would make a tangential detour driven by the centripetal force if agent j (the yellow one in Fig. 2) is in the current walking area of agent i and the distance of agent i, j is smaller than 0.5m.

In summary, a passenger could be driven by an exclusive force from other passengers, and sometimes a centripetal force as well as.

$$\vec{\mathrm{F}}_{i,t}^{\mathrm{centri}} = \mathrm{m}_i * v_{i,t}^2 / r_{i,j} \quad (7)$$

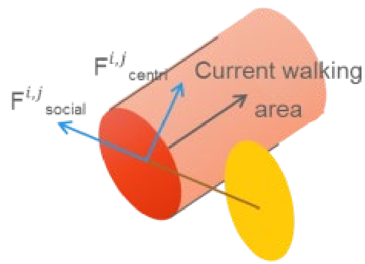
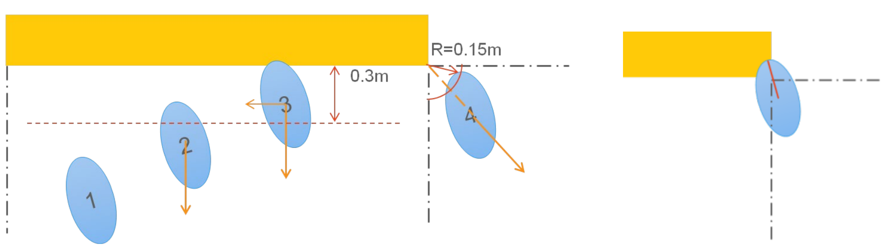


Fig. 2: Centripetal force

2.2.4. Wall Force

According to the relative position of a passenger and the walls, the repulsive force between them should be calculated in different ways. In the first case, passenger i is close to and in front of a wall (agent 1,2,3 in Fig. 3a), he would be driven by a repulsive force $\vec{F}_{i,t}^{\mathrm{wall\_front}}$, defined in equation 8. Similar to social force, the working scope of wall force is less than other scenes such as a passage. In our model, we set it as 0.3m.

In the second case, passenger i is close to a convex corner of an obstacle (agent 4 in Fig. 3a), the repulsive force could be defined as equation 9. In a carriage, such convex corners are the lateral corners of seats. The detour repulsive force has not been considered in other SFM. This can cause a larger overlap between the agent and the seat in a crowded carriage, as shown in Fig. 3b, which is unrealistic. As observed in metro trains, passengers show weak rejection to the seat corner, and they often walk close to such corner. Therefore, the detour repulsive force works with the distance of 0.2m.



(a) (b)

Fig. 3: Centripetal force

$$\vec{F}_{i,t}^{\mathrm{wall\_front}} = \vec{F}_{i,w,t}^{\mathrm{social\ repulsive}} + \vec{F}_{i,w,t}^{\mathrm{pushing}} + v_{i,\mathrm{w},t}^{\tau} * \vec{F}_{i,w,t}^{\mathrm{friction}} \quad (8)$$

$$\vec{F}_{i,t}^{\mathrm{wall\_corner}} = \vec{F}_{i,w,t}^{\mathrm{social\ repulsive}} + \vec{F}_{i,w,t}^{\mathrm{pushing}} \quad (9)$$

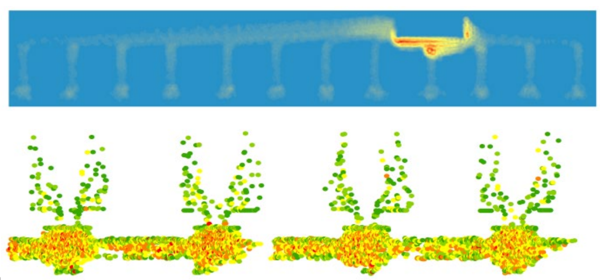
where $\vec{F}_{i,w,t}^{\mathrm{social\ repulsive}}$ is the psychological repulsion between pedestrians i and wall w, $\vec{F}_{i,w,t}^{\mathrm{pushing}}$ and $\vec{F}_{i,w,t}^{\mathrm{friction}}$ are the extrusion force and friction force when pedestrian i makes a contact with wall w, $v_{i,w,t}^{\tau}$ is the tangent velocity of passengers i in direction of wall, if the tangent velocity is 0, then the friction force would be 0.

A passenger may be driven by several forces from different walls at the same time. In our simulation, only the nearest wall or corner is considered. This is consistent with the passengers' strategy of giving priority to solving the most urgent situation in real life.

3. Simulation

The simulation program is developed by C++, which is an object-oriented programming language. In the simulation system, personal characteristics (body size, mass, expected speed, etc.) are considered with certain random distributions. The alighting passengers, the boarding passengers and the through-standees are marked by a property variable. In the visual interface, they are represented as red, blue and green respectively. The simulator could record the kinematic parameters of each agent during simulation in the individual level, such as passenger ID, location coordinates, speed, force and local density, as well as the key points in time of different groups. In the light of these data, we can capture some characteristics of their activities both on platforms and in the trains, as shown in Fig. 4.

Based on the micro-simulation model developed in this paper, simulation experiments that include a wide range of alighting and boarding group sizes and ratios were run. The evacuation simulation experiments indicate that the flow rate of the vehicle door is varied with passengers' expected speed, the number of evacuees and the passing time, rather than a constant. The local velocity outside the door can explain 90% variation of the flow rate. When the desired speed is less than 1.5 m/s, the maximum and average speed of getting through the door can be stabilized at 1m/s and 0.8m/s, respectively. Beyond that, the greater the desired speed, the higher the get-through speed.



a)

b)

Fig. 4: (a) Congestion of alighting passengers near staircase. (b) Density distribution of the boarding passengers.

Passengers' movement follows the principle of "get off and then on". It is an important issue to tell the time when stage Ⅱ finished and stage Ⅲ starts. Based on the observation in metro stations, stage Ⅲ would begin if there is no alighting passengers in a range of 0.5m around the door. Due to the uncertainty of passenger attributes and behaviour, for each door, the start time of stage Ⅲ may be slightly different and it needs to make a dynamic identification.

The movement parameters of agents are updated by Gear method. Due to the limited motor ability of passengers, the velocity at any time should be less than the expected speed. To avoid some sudden and huge changes in the movement parameters caused by great force, the acceleration and one-step displacement should also be restricted. In addition, the volume compression of the human body cannot exceed the limit value (20%). An agent should remain in place when he is not driven by any force.

The alighting and boarding process occurs at a typical island platform. There are two sets of escalators/stairs connecting with the underground hall, as shown in Fig. 6. It is assumed that passengers have no preference for these two sets of escalators/stairs and they would choose the nearest one. As the platform is symmetrical, we simulate only half of the platform on one side. This scenario is also applicable to the analysis of side platforms.

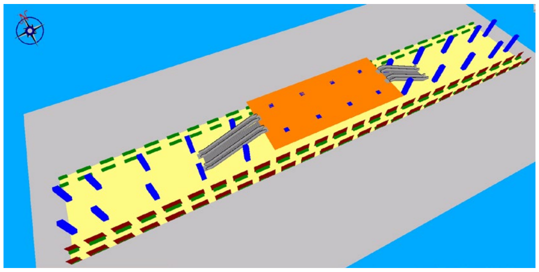


Fig. 3: The simulated island platform

The model was verified in the view of three aspects: the value of extrusion pressure of alighting passengers while getting on the train; the duration of alighting/boarding with different density; the relationship between velocity and density. Simulation experiments denote the model considered basic motivation and dynamic conditions and show perfect performance in the calibration run for the validation.

4. Discussion

This section explores the impact of some certain structural facilities and organizational measures on the movement of alighting and boarding. To evaluate the effectiveness of these design and managing measures, an index evaluation system was established in terms of comfort, smoothness and efficiency.

4.1. Waiting Area

The waiting area of the platform is usually marked as yellow or white waiting lines. Boarding passengers would queue up according to the marked position and their queue locations determine the available space for the alighting passengers. To find out the most suitable queuing position, five groups of simulation experiments were conducted and a control group was set up.

The longer the distance between the two waiting lines in front of a door, the higher the efficiency of getting off that was reached. But when the distance is longer than 10 cm, the efficiency is almost constant.

According to human perception of pressure, physical extrusion pressure is divided into four levels, as shown in Table 1. The closer the two queue lines, the greater the force will be, and the longer the force worked. And this may lead to discomfort. It is already quite comfortable in the case of 10 cm outward from the door.

Therefore, queuing up outward 10 cm from the door would achieve both efficiency and comfort.

Table 1: Duration of physical extrusion pressure in the process of alighting.

physical extrusion pressure	20 cm inward	10 cm inward	align with the door	10 cm outward	20 cm outward	30 cm outward
175 N-247 N	49.50 s	23.41 s	10.37 s	2.84 s	1.9 0s	0.17 s
247 N-600 N	7.49 s	2.36 s	0.90 s	0.13 s	0.1 0s	0
600 N-2500 N	15.02 s	3.79 s	1.52 s	0.21 s	0.12 s	0
>2500 N	7.6 0s	1.29 s	0.35 s	0.11 s	0.04 s	0

4.2. Pillar on Platform.

The existence of a pillar on the platform leads to low efficiency, with longer time to get off. This is mainly because of the low speed and increased crowd density between the pillar and the door. U is smoothness of speed, defined as equation 10. The doors near pillars have larger values of U, which means that the passengers suffer more interference.

$$\mathrm{U} = \frac{1}{N}\sum_{\alpha} \frac{\overline{\left(\vec{v}_\alpha - \overline{\vec{v}_\alpha}\right)^2}}{\overline{(\vec{v}_\alpha)^2}} \qquad (0 \le U \le 1) \tag{10}$$

where $\overline{\overrightarrow{v_\alpha}}$ is pedestrian's space speed (m/s), which means the ratio of distance to time in a certain space, and $\overrightarrow{v_\alpha}$ is pedestrian's instantaneous speed (m/s), which means the speed of a pedestrian through a certain point.

4.3. Handrail in Train

Inside a carriage, a handrail may be built in the seat area or the door area, or both. Simulation experiments show that the handrail has little influence on the time of alighting and boarding. The difference is within 5%, less than 1 second, which can be neglected.

Considering the complexity of the facilities and the environment, pedestrians do not always walk the shortest distance. Distance curve coefficient is defined as the ratio of walking distance l to the shortest linear distance d, indicating smoothness and stability:

$$R = \frac{l}{d} \tag{11}$$

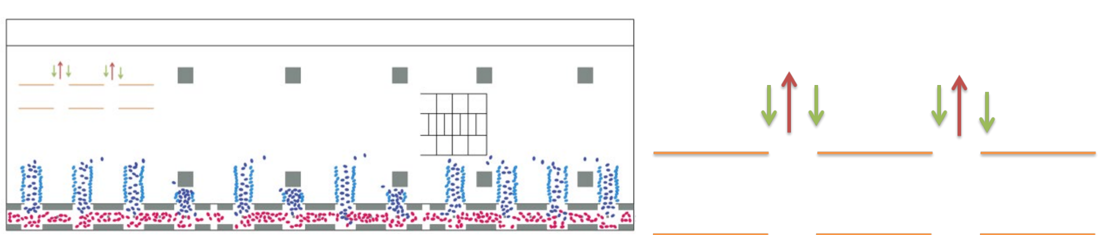
Investigation of passengers' alighting process indicate that the value of R is in the range of [1.2~2.6]. A handrail in the door area (Fig. 5 shows the passenger path) can make lower value of R, while a handrail in the seat area has little influence. Compared with the car equipped with handrails in both areas, the R value of a car with a handrail only in the door area could reduce by 1.4%, and for a car with a handrail only in the seat area, 4% reduced. So, the handrail is disadvantageous for the passenger's walking path. But it can help passengers maintain balance. Therefore, it is recommended to replace the handrail by a suspended handle.

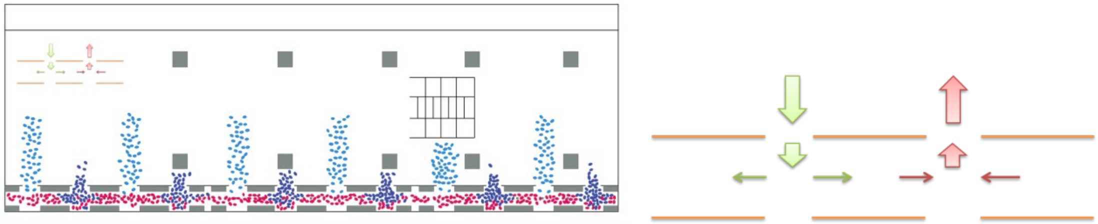
Fig. 5: The simulated island platform

4.4. Separated Alighting and Boarding

Finally, we put forward a creative organization mode to minimize the disturbance between alighting and boarding passengers. The two movements were separated (Fig. 6b) and would take place in the two adjacent vehicle doors simultaneously. In Fig. 6b, the average drop time is reduced by 2.5 seconds; passengers can leave the platform faster through the stairs, reduce queuing and congestion; the distance curve coefficient is decreased by 38%. Therefore, this measure has better performance in general.

a)





b)

Fig. 6: (a) "Get off and then on" at the same door. (b) Boarding and alighting movements are separated by the adjacent door, with less conflict, more comfortable and more efficient.

5. Conclusion

We developed a multi-agent model in micro-level to simulate passenger movement in boarding and alighting. It has good performance, even in some complex scenes, and provides an effective method for design and passenger organization in metro stations. The model presented in the paper exhibits a range of complex, collective phenomena. It also captures individual characteristics and collective group behaviors during the processes of alighting and boarding movement that were once difficult to model. The agents appear to exhibit reasonable intelligence and diversity during the process of alighting and boarding, which includes some characteristics of actual persons. Field data and simulation output show the validity of this model to emulate passenger movement. Some measures to make passengers get on and off trains smoothly were proposed in three aspects. The first one is the way of queueing up on the platform before getting on. The second aspect is the structure facilities, specifically, the vertical handrail in train and the pillar on platform. Finally, we put forward a creative organization mode to minimize the disturbance between alighting and boarding passengers. The two movements were separated and would take place in the two adjacent vehicle doors simultaneously. However, calibration and validation of the simulation model presented in the paper have limited field data and experiments. Further research has to be done to perform more observations and extend the calibration and validation of the model. Further study of the model should include the collective behavior of passenger distribution on the platform, changing target doors and other detailed behavior that may influence alighting and boarding performance.

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