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Study on strategies for alighting and boarding in subway stations

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\textbf{ABSTRACT}

With its high infection rate, COVID-19 has swept the globe and brought great challenges to social life and economies. As an essential form of public transportation, the Beijing subway plays an important role in transportation systems. In traditional subway organizations, all one-sided doors of a train carriage are employed for passengers' alighting and boarding. A higher risk of COVID-19 infections may be attributed to inevitable bidirectional conflicts at doors with higher passenger volumes. Moreover, quantitative analyses for this problem and corresponding solutions are limited in recent studies. In this research, conflicts at carriage doors are analyzed using a cellular automaton (CA) based model. Four schemes to separate alighting and passenger boarding into separate doors are investigated. The performances of different schemes with various alighting and boarding passenger ratios are simulated with the software package Legion Studio. Both macroscopic and microscopic parameters to characterize passenger conflicts are obtained for analysis. The separation of alighting and boarding passenger flows yields the desired reduction in bidirectional conflicts, which further limits the probability of infectious disease exposure. This is an important reference to improve current practices and provide specific measurements of passenger organization under abnormal situations.

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1. Introduction

The coronavirus disease of 2019 (COVID-19) first broke out in late 2019 in Wuhan, China. It turned out to be a global pandemic in a relatively short time due to its high infection rate. A peak in the coronavirus outbreak was seen in the second half of March in China. Moreover, three infection modes (droplet, aerosol, and fomite) for COVID-19 were confirmed, which indicates a high risk of infection for individuals. After the outbreak, Chinese governments (central to local) initiated primary healthcare responses to the pandemic. After 76 days, the government lifted the lockdown in Wuhan on 8th April, which is the city that was the hardest hit. This seemed to be a positive signal to curb the pandemic in China.

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However, another outbreak in Xinfadi, Beijing’s largest agricultural wholesale market, from 11–18 June sparked alarm in the metropolis with 183 confirmed cases [1]. This brought an end to a record of no new infection cases in 56 consecutive days. In recent years, the daily passenger volume of subways in Beijing exceeded 10 million with a total length of subway transport of 637 kilometers. The Beijing subway system has been the primary transportation mode for three million citizens, even during the critical time of COVID-19 in March [2]. This number is quite inappreciable during other periods. To cope with the aftermath of COVID-19, the operating company of the Beijing subway implemented feasible guidelines for pandemic prevention. The guidelines included wearing masks, temperature measurements, train and station disinfection, and passenger protection. This ensured the safety, efficiency, and orderliness of passenger alighting and boarding during this typical period. However, field observations have revealed frequent conflicts (frontal and side) between alighting and boarding traffic flows at carriage doors in the Beijing subway as among the common methods of proximity, which evidently increased the risk of viral transmission. Hence, the objective of this paper is to investigate conflicts between alighting and boarding traffic flows and to explore the alternatives to minimize in-crowd viral transmission rate. The outcome of this study contributes to improve the efficiency and serviceability of subway passenger management and organization under unusual conditions, such as epidemics and disasters.

Over the past decade, most research in passenger management and organization has emphasized the analysis of passenger flow optimization and headway minimization [3–9]. A considerable amount of recent studies for passenger flow organizations have focused on passenger optimization [10,11]. Research by Guo et al. [12] showed that unidirectional and bidirectional pedestrian flows may be significantly affected by the direction of passengers who are one meter ahead in unidirectional walking. Zhang et al. [13] uncovered that the maximum capacity of unidirectional flow is larger than that of all bidirectional flows (dynamic multi-lanes, stable separated lanes, balanced flow ratios, and unbalanced flow ratios). Studies have also investigated pedestrian flows at different facilities of the subway station, such as passageways, platforms, and stairs [14–16]. However, little attention has been given to conflicts of alighting and boarding passenger flows at carriage doors. In particular, there is little research on alighting and boarding passenger flow organization of carriage doors during infectious disease outbreaks.

Models for passenger organization have focused primarily on headway minimization. Kraft [17] and Rodríguez [8] considered alighting and boarding passenger flows as the main factors that affect the flow times to optimize the dwell time model. Zhang et al. [18] analyzed the micro-characteristics of alighting and boarding flows using a video log. They established the cellular automata (CA) model to simulate the alighting and boarding flows and demonstrated its effectiveness on microscopic pedestrian flow modeling. Moreover, a study by Wong et al. [19] experimentally considered pedestrian bidirectional stream conflicts with oblique intersecting angles. The exploration into pedestrian organization for alighting and boarding flows in the subway train and assessments of the impact of vertical handrails in the carriage and at doors was considered by Sebastian and Rodrigo [20]. However, prior studies have not combined present approaches with simulation analyses.

This paper examines the subway carriage alighting and boarding strategies under low passenger flows and high infection risks of at subway stations during the COVID-19 pandemic to further elevate their efficiency, lower the risk of infections by reducing proximity, and reduce the length of queues at subway stations. This article not only fills the gap of studies on passenger organization in subway carriage doors but provides specific and workable guidance measures for alighting and boarding under primary healthcare responses. The previously developed CA model based on legion simulations is adopted in this paper, which has been employed in many pedestrian simulation examples. Furthermore, several organizational schemes are proposed and the corresponding experiments were performed under the assumption of an infectious disease outbreak. The best organization scheme is singled out accordingly, which is beneficial for major public health events.

This paper is organized as follows. Section 1 introduces the background and current research conclusions of alighting and boarding passenger flows. Section 2 describes the methodology in detail. Section 3 lists all the analytical results of the passenger flow characteristics under different optimal strategies and discusses the optimal strategic differences. Section 4 concludes this study.

2. Methodologies

Subways and buses are the two most commonly used public transportation modes in cities and possess similar characteristics of passenger organization as both have more than one carriage and two or more doors for alighting and boarding in each carriage. In contrast with subway doors for both boarding or alighting during the COVID-19 pandemic, the organization of buses was changed (i.e., a door only for either boarding or alighting) during 2006 in Beijing, which has secured better efficiency and safety [21]. Yu et al. concluded that the separation of alighting and boarding can decrease the number of friction surfaces, improve the flow rate, and lower the average delay [22]. Therefore, this study investigates mitigation techniques for alighting and boarding passenger conflicts in subways, which considers the separated strategy of alighting and boarding for the bus system (one-way flow at any door).

In the Beijing subway system, a train consists primarily of six carriages, and each of which has four doors on the same side. As depicted in Fig. 1, there are six combinations of alighting and boarding alternatives ($C_2^6$) based on the actual layout of the subway train carriage. The A0 case is for alighting and boarding passenger flows that share the same carriage door, which is the present organization pattern in the Beijing subway system. In contrast, A1–A6 are different organizational
alternatives for one carriage. In A1, alighting passenger flows use the first and second doors and boarding passenger flows use the third and fourth doors from left to right. In A2, boarding passenger flows use the first and third doors from the left. In A3, boarding passenger flows use the first and fourth doors from the left. In A4, alighting passenger flows use the first and fourth doors from the left. In A5, alighting passenger flows use the first and second doors and boarding passenger flows use the third and fourth doors. In A6, alighting passenger flows use the first and third doors from the left. Therefore, after removing symmetric scenarios, four practical combinations are established as alternatives against the basic scenario currently in practice. Consequently, there are five passenger organization schemes in total, illustrated as A0–A4 in Fig. 1.

Passenger flows for different alternatives were modeled in this study using the CA principle and implemented in Legion Studio. Analyzing the microscopic and macroscopic passenger behavior parameters identified an optimized passenger organization.

2.1. Passenger alighting and boarding at train carriage doors

Field observations indicate that there are five phases of passenger movements for alighting and boarding, as shown in Fig. 2:

Phase 1: Continuous arriving passengers (boarding passenger flow) queue at the two sides of the carriage door, as shown in Fig. 2a. The queue is a straight line and the left passageway is for oncoming alighting passenger flows.

Phase 2: When the train is arriving at the platform, onboard passengers gather toward the carriage door for alighting off the train, which forms the passenger flow. Meanwhile, the boarding queues begin to move towards the carriage doors, which results in a skewed queue and narrowed passageway.

Phase 3: At the arrival of the train, onboard passengers start to alight, and conflict occurs when the alighting flow attempts to move through the boarding queue and exit the platform.

Phase 4: Conflict between alighting and boarding flows does not stop when the last passenger alights and boarding flow dominates the boarding process. The zone where conflict occurs is defined as the conflict zone below.

Phase 5: At the beginning of the situation, boarding flows are affected by the alighting flow to get on the train after the alighting flow moves through the boarding queue. Then, the boarding flow gets on the carriage without conflict.

2.2. Cellular automata based simulation model

It is complicated and circumscribed to study pedestrians through analyses and experiments due to their complex behaviors [21]. Consequently, computerized simulations are a prevalent approach. Two extensively used models for pedestrian behavior studies, which are performed here, include the social force model and traffic flow-based models (e.g., cellular automata) [21,23]. The application of the social force model, better reliability notwithstanding, is exceedingly complex as it involves interactions between pedestrians and requires quantifying these interactions, such as from various forces. In recent years, the discrete CA model, which conforms to the characteristics of pedestrian flow, has been introduced to successfully simulate dynamic pedestrian behaviors [24,25].

The CA concept was proposed in the 1940s by Neumann [26,27], which can simulate the dynamic process of real-world systems and how pedestrians achieve time–space movement, especially in complex pedestrian flows. Several commercial software applications have been created to implement the CA [28]. A pervasive application called Legion Studio was provided by Still and has been employed in several events, such as the 2008 Beijing Olympic Games, 2010 Asian Games, and the 2010 Shanghai World EXPO [29–31]. Legion Studio considers multiple pedestrian characteristics, including originality, personal belongings, walking speed, and infrastructure layout, which may affect their movement [28].
2.3. Models to simulate passenger flow

2.3.1. CA model

The CA is composed of a series of the CA, cellular space, and corresponding rules [32–34]. The CA moves from one cell to one of its neighbors through a set of rules in the designated cell space. For each step, the automaton is set to move up to one cell. In the model, one cell has two or more states. As an example, if there are two states {0, 1} of the cell, in which 0 is unoccupied and 1 is occupied, the entity is defined as State 1.

The CA is integrated into and can be implemented through the Legion Studio as follows. The cellular space is defined as a 2D W×W cell, where W is the size of the system as determined from the users and depends on the input scenario. Each pedestrian occupies an area of a 3×3 grid, which is defined as a cell. The size of each cell is 0.1 m×0.1 m and for the pedestrian is 0.5 m×0.5 m in the simulation. Such an approximately sized pedestrian yields a perfect outcome in the performance of a high-density crowd.

In Fig. 3, the C₀ cell represents the original or initial position of a pedestrian, and cells C₁–C₈ are defined as its neighbors. According to pedestrian movement rules, the pedestrian moves towards the optimized adjacent cell (one in C₁–C₈). The comparison in Fig. 3a shows that C₀ moves into C₁ and becomes a new C₀ cell, and the neighbors of the new C₀ are simultaneously refreshed. Thus, the neighbors to the C₀ change each step.

According to Ref. [33], the rule for bidirectional conflicts is illustrated with a two-pedestrian example (A and B) in Fig. 3b. The target cell and movement probability of pedestrians are determined from the surrounding environments (the number of passengers, speed of passengers, distance from the target, etc.) and the moving speed of the passengers,
respectively. Passengers under surrounding environments move to the target cell at relatively high speeds. In the graphical example, two passengers initially move inwards and outwards without restriction. When they approach each other, several potential conflict cells may emerge. These conflict cells are occupied in completion by the passenger with the highest probability [35–37]. For example, in Fig. 3b, pedestrians A and B compete for occupation if there is no conflict. In the competition (i.e., \( P_{A6} \) vs. \( P_{B1} \), \( P_{A7} \) vs. \( P_{B2} \), and \( P_{A8} \) vs. \( P_{B3} \)), pedestrian A succeeds (\( P_{A7} > P_{B2} \)) and moves to the yellow cell, and pedestrian B has to move to another cell with the second-highest probability. A comparatively low probability of passengers moving around is detected once they arrive in the waiting zone, which is in contrast to those outside the waiting areas. This setting reflects the situation during the COVID-19 pandemic, which reduces conflicts caused by frequently changing target waiting zones.

2.3.2. Legion simulation

Legion Studio can simulate several CAs in one step. The rules in Legion conform to the Objective, Motility, Constraint, and Assimilation (OMCA) rules [38]. These rules can be described by an optimal algorithm that seeks the minimal effort route under the non-collision constraint conditions, which can be achieved through a type of simulated annealing. Passengers in the simulation are characterized by the speed distribution, luggage size, inwards-passerenger travel origin, and outwards-passerenger travel destination [39]. With an overview of previous research, the mean free speed of the passenger flow is set to 1.34 m/s with a standard deviation of 0.26 m/s [27].

The Legion simulation consists of independent problem-solving entities [20]. Each entity’s path is constrained by the least-effort algorithm after considering the length, total time, and effort. For each cell, the state depends on the neighbors around it. These entities move around a two-dimensional computer-generated landscape before reading and reacting to changes in that environment, including responses to the behaviors of other entities [39]. Legion Studio supports a convenient and visible approach to this study, as it not only designs different traffic volumes and organization alternatives but also prevents interference from confounding factors in the environment.

2.3.3. Basic scenario

The basic scenario of the model is a train carriage with four doors on each side based on a train from Subway-Line One [40]. As is shown in Fig. 4a, the width of the carriage is 2.8 m, its length is 19 m, and the width of each sliding door is 1.5 m. Only one carriage and the front areas of the four doors are considered here. To standardize and simplify the scenario model, it is designed as an assignment of the 2D space pedestrian movement in one carriage. Additionally, the conflict zone on the platform, including the waiting zone and the passageway, is matched to simulate the alighting and boarding processes, as illustrated in Fig. 2. The widths of the conflict zone, waiting area, and passageway are 2.5, 0.5, and 1.5 m, respectively.

To analyze the conflict in the flow, the parameters of time, distance, density, and travel speed are collected in the analysis line and zone established in the analyzer model of Legion Studio. For the scheme shown in Fig. 4b, two analytical lines are designed to output the average time and distance taken to cross them. The average spot speed of the passengers and their density in the detection zone can be determined from the analysis zone. Furthermore, the endpoint of passenger movements is the carriage for boarding or the absence from the platform for alighting.

A two-level analysis of the conflict influences and the performance of the alternatives are considered. One level is the conflict study, which explores the alighting and boarding flow parameters to discuss the conflict influences for the different flows at the conflict zone in front of the door. The second is the simulation system level, to discuss the impact of diverse alternatives, which considers the passenger parameters in the simulation scenario scale.
2.4. Passenger composition

Field observations were conducted at several subway stations in Beijing at various periods (see Table 1). The volumes of alighting and boarding passengers can be categorized into three types: Alighting flow larger than boarding flow, boarding flow larger than alighting flow, and balance between the two flows. Based on three types of passenger volumes, the ratio of traffic volume for the alighting and boarding passengers is simplified as 2:1, 1:2, and 1:1. To identify the impacts from alighting and boarding passenger flows, the volume of each ratio unit 1 is from 1 to 35 and unit 2 is from 2 to 70. The total flows of the ratios 1:2 and 2:1 is larger than the volume of the rate of 1:1 for one-third.

3. Analysis of simulation results

The parameters to measure the performance of passenger flows, including time, density, distance, and level of service, are investigated based on the Legion Studio simulation results [41,42]. The flow conflict is discussed in the analysis of the conflict zone. These parameters are discussed at the simulation system level.

In the simulations, a saturation of passenger flow occurs when 26 passengers are alighting at the 1:2 level and 52 passengers at the 2:1 level. The parameters before the saturated flow are analyzed. The three microscopic parameters of speed, density and time, and the three macroscopic parameters of the level of service (LOS) [40], level of interaction (LOI) [43], and conflict rate (CR), are selected as the analysis elements. The LOS is defined as a service quality standard that passengers feel while walking [44] and is a quantitative measure for the quality of pedestrians based on the number of passengers per square meter per unit time, which is expressed as the rate of change in the density [39,45]. The LOI is defined as an indicator to measure interactions between alighting and boarding passengers at metro stations [43]. The CR indicates the ratio of the total number of conflict streamlines to the total number of streamlines between alighting and boarding passengers as an alternative.

A two-way ANOVA is employed to compare the performances of the ratios and different alternatives through the influence of the passenger parameters. The independent samples of the passenger flow are assumed/approximated to follow a normal distribution.
Table 1
Traffic volume of passenger at one door.

| Location                  | Alighting volume | Boarding volume | Location                  | Alighting volume | Boarding volume |
|---------------------------|------------------|-----------------|---------------------------|------------------|-----------------|
| Huixin Xijenankou Station |                  |                 | Jinsong Station          |                  |                 |
| (12/5/2020, 5–6 p.m)      |                  |                 | (13/5/2020, 7–8 a.m)     |                  |                 |
| 3                         | 10               |                 | 23                        | 4                |                 |
| 6                         | 7                |                 | 29                        | 4                |                 |
| 4                         | 16               |                 | 28                        | 3                |                 |
| 3                         | 3                |                 | 29                        | 3                |                 |
| 2                         | 7                |                 | 29                        | 4                |                 |
| 1                         | 4                |                 | 24                        | 6                |                 |
| 3                         | 10               |                 | 35                        | 4                |                 |
| 6                         | 7                |                 | 30                        | 4                |                 |
| Xidan Station             |                  |                 |                           |                  |                 |
| (14/5/2020, 5–6 p.m)      |                  |                 |                           |                  |                 |
| 19                        | 19               |                 | 41                        | 2                |                 |
| 16                        | 19               |                 | 42                        | 0                |                 |
| 16                        | 21               |                 | 35                        | 2                |                 |
| 9                         | 16               |                 | 25                        | 2                |                 |
| 2                         | 8                |                 | 27                        | 5                |                 |
| 2                         | 5                |                 | 28                        | 4                |                 |
| Huijialou Station         |                  |                 |                           |                  |                 |
| (13/5/2020, 7–8 a.m)      |                  |                 |                           |                  |                 |
| 18                        | 4                |                 | 31                        | 2                |                 |
| 12                        | 4                |                 | 33                        | 2                |                 |
| 14                        | 6                |                 | 31                        | 3                |                 |
| 11                        | 6                |                 | 32                        | 1                |                 |

Table 2
Percentage of parameters increasing value for unidirectional passenger flows.

|                   | Alighting | Boarding |
|-------------------|-----------|----------|
| Ratio             | Average speed | Average density | Average time | Average speed | Average density | Average time |
| 1:1               | +12.9%     | −24.9%    | −12.3%       | +31.4%       | −47.7%        | −11.2%       |
| 1:2               | +22.4%     | −18.9%    | −14.0%       | +36.7%       | −53.7%        | −13.4%       |
| 2:1               | +93.9%     | −15.6%    | −10.1%       | +54.4%       | −50.0%        | −12.1%       |

3.1. Analysis of the conflict zone

The results in Fig. 5 reveal a negative outcome for most of the different average densities and times, which indicates a smaller mean density and time in the new schemes compared with the control group (A0). Positive results in most cases for different average speeds were detected, which is indicative of a higher average speed in the new schemes than in the control group (A0). Taken together, the increased speed is attributed to the separated passenger flows.

Table 2 shows notable changes in the parameters (average speed, average density, and average time) of alighting and boarding passengers, especially for boarding. The table reveals a marked rise in boarding speeds by over 30% and a decline in densities by over 45%. This suggests a more prominent impact on the boarding passenger flow than alighting when using the new schemes. Differences in passenger characteristics at peak hours are considered. The mitigation of density significantly reduces conflicts, releases the pressure of the station devices, improves safety by lowering the density, and increases efficiency.

3.2. Time

The average time for different schemes is presented in Fig. 6, in which an inclination of passengers selects the shortest route to access their endpoints. The A0 (current alighting and boarding scheme) obtained the shortest average time as passengers are allowed to choose the routine based on their will. The time increases for larger passenger volumes. The average time of A4 is higher than the others as the alighting doors are designed in the middle part of a carriage, which has a long way to alight. Furthermore, the increased time achieves a mean of 10.6s.

The results of the test show that there is a significant impact of the schemes on the average time ($F(4, 136) = 12.07386$, $p < 0.05$), which does not exist in the ratios ($F(2, 68) = 1.72487$, $p = 0.18$). Furthermore, significant differences are obtained between alternatives 1–4 and 0 at the 0.05 confidence level based on the statistical test shown in Table 3. The largest
Table 3
Statistical test of time parameters.

| Group | Time     | T value | Probability   | Alpha | Significance |
|-------|----------|---------|---------------|-------|--------------|
| A1 A0 |          | 17.93633| 4.67339E−40   | 0.05  | True         |
| A2 A0 |          | 21.47689| 2.65415E−49   | 0.05  | True         |
| A2 A1 |          | 3.54056 | 0.00515       | 0.05  | True         |
| A3 A0 |          | 19.25594| 1.40445E−43   | 0.05  | True         |
| A4 A0 |          | 26.67127| 1.20857E−61   | 0.05  | True         |

Significance indicates that the mean difference is important at the 0.05 level.
Note: Only the significant results are shown.

A significant difference is observed in A4, followed by A2 and A3. The A1 data are nearest to those of A0, but differences are also detected between them.
Fig. 6. Average time of passenger flows in different alternatives.
3.3. Travel distance

As shown in Fig. 7, longer travel distances are found as available doors for passenger alighting and boarding are restricted after separating the bidirectional passenger flows, which results in an increased time. The travel distance increased with the passenger flow volume in A0. However, the travel distances for other schemes changed only slightly with the flow, which implies the travel distance in separated alternatives may not be affected by passenger volume. It is assumed that these travel distances are accompanied by a high steadiness, which can be easily controlled.
Table 4
Statistical test of travel distance parameters.

| Group | Travel Distance | T value  | Probability | Alpha | Significance |
|-------|-----------------|----------|-------------|-------|--------------|
| A1 A0 | 37.15913        | 3.17407E−146 | 0.05 | True |
| A2 A0 | 41.62591        | 3.8609E−165 | 0.05 | True |
| A2 A1 | 4.46678         | 9.786E−5    | 0.05 | True |
| A3 A0 | 35.25277        | 8.009E−138  | 0.05 | True |
| A3 A2 | −6.37314        | 9.786E−5    | 0.05 | True |
| A4 A0 | 62.7078         | 7.336E−241  | 0.05 | True |
| A4 A1 | 25.54867        | 2.543E−92   | 0.05 | True |
| A4 A2 | 21.08189        | 2.026E−70   | 0.05 | True |
| A4 A3 | 27.45503        | 1.458E−101  | 0.05 | True |

Significance indicates that the mean difference is important at the 0.05 level.
Note: Only the significant results are shown.

Table 5
Statistical test of speed parameters.

| Group | Speed | T value  | Probability | Alpha | Significance |
|-------|-------|----------|-------------|-------|--------------|
| A1 A0 | 16.85238 | 4.213E−37 | 0.05 | True |
| A2 A0 | 18.03539 | 2.525E−40 | 0.05 | True |
| A3 A0 | 17.65452 | 2.708E−39 | 0.05 | True |
| A4 A0 | 20.98533 | 4.654E−48 | 0.05 | True |

Significance indicates that the mean difference is important at the 0.05 level.
Note: Only the significant results are shown.

Table 6
Statistical test of density parameters.

| Group | Density | T value  | Probability | Alpha | Significance |
|-------|---------|----------|-------------|-------|--------------|
| A1 A0 | −3.08638 | 0.02366 | 0.05 | True |
| A2 A0 | −4.06558 | 7.313E−4 | 0.05 | True |
| A3 A0 | −3.73214 | 0.00259 | 0.05 | True |
| A4 A0 | −4.27924 | 3.124E−4 | 0.05 | True |

Significance indicates that the mean difference is important at the 0.05 level.
Note: Only the significant results are shown.

Similar statistical results of the average time are reflected in the analysis of the travel distance. That is, no significant main effect of the ratios (F(2,680)=1.12029, p=0.33) is found, but the new schemes can significantly impact the average travel distance (F(4,136)=1020.37053, p<0.05). As shown in Table 4, the five alternatives could be statistically classified into four groups ranked for an increasing travel distance: (1) A0; (2) A1 and A3; (3) A2, and (4) A4.

3.4. Passenger speed

Compared with A0 in Fig. 8, higher average speeds were recorded for A1–A4, where A4 seemed to be the most optimistic scheme at the average level. In line with the results of the two above-mentioned indicators, there are significant primary effects of the alternatives on the average passenger speed (F(4,136)=558.71211, p<0.05). Moreover, closer inspection detects a higher mean speed for A1–A4 than A0. However, no significant differences among A1–A4 (see Table 5) were observed. Although the ratios still have no significant primary effect on the average passenger speed (F(2,68)=0.24605, p=0.78), the speeds of the alternatives decrease with increasing passenger volume. The mini-speed is more than 0.6m/s when A0 is lower than 0.3m/s.

3.5. Density

The difference between A0 and the other scenarios is used to examine the impact of the density. As shown in Fig. 9, a larger difference indicates an increased volume. Table 6 illustrates a lower average density of A1–A4 compared to A0. Similar to the average passenger speed, the significant primary effects of the schemes on the average density are determined (F(4,136)=569.67602, p<0.05). However, there are still no significant differences among the average densities of A1–A4.
3.6. Level of service

The concept of LOS was proposed by Fruin [40] and is used to evaluate the facility through pedestrian feelings of comfort. Six degrees of serviceability are represented as different colors in Fig. 10, which presents the results of the high
Fig. 9. Average density of passenger flows in different alternatives.

densities for schemes A1–A4 at the simulation space with the LOS. The alighting LOSs for all four schemes are at the A level. The density in front of the boarding door for A1 is higher than A2–A4 and A3 is higher than A2 and A4. The A4 has the lowest density in front of the boarding door. Compared with A1–A3, the alighting doors of A4 are convenient
Fig. 10. High density of the schemes based on the Fruin LOS.

Table 7
Results of LOI for different alternatives.

| Alternatives | Type of queue for boarding passengers | Formation of lanes for alighting passengers | R (boarding / alighting) | LOI |
|--------------|----------------------------------------|---------------------------------------------|--------------------------|-----|
| A0           | Clustered at the side and in front of door | Between 1 and 2 lanes                        | 1                        | Medium |
| A1           | Clustered or queuing at the side of door | 2 lanes                                     | <0.25                    | Low |
| A2           | Clustered or queuing at the side of door | 2 lanes                                     | <0.25                    | Low |
| A3           | Clustered or queuing at the side of door | 2 lanes                                     | <0.25                    | Low |
| A4           | Clustered or queuing at the side of door | 2 lanes                                     | <0.25                    | Low |

Table 8
Results of CR for different alternatives.

| Alternatives | Number of boarding streamlines | Number of alighting streamlines | Total streamlines | Conflict streamlines | CR (%) |
|--------------|-------------------------------|-------------------------------|-------------------|----------------------|--------|
| A0           | 8                             | 4                             | 12                | 12                   | 100    |
| A1           | 4                             | 4                             | 8                 | 0                    | 0      |
| A2           | 4                             | 4                             | 8                 | 0                    | 0      |
| A3           | 4                             | 4                             | 8                 | 0                    | 0      |
| A4           | 4                             | 4                             | 8                 | 0                    | 0      |

for passengers leaving the platform with the highest detected walking speed as they are at the end of the carriage. However, the alighting flow streams for A1–A3 are interwoven with boarding flow streams to some extent. As a result, A4 is considered the best strategy for alighting and boarding on subway platforms.

3.7. Level of interaction

To evaluate conflicts, the LOI is used to measure interactions between alighting and boarding passengers [43], which includes three classifications (low, medium, and high) based on the types of queues and lane formation. The LOIs for the five alternatives (A0–A4) are proposed in Table 7 according their classification principle. A1–A4 exhibit better results with a lower LOI compared with A0. Thus, the new schemes have greatly reduced conflicts and are considered practical.

3.8. Conflict rate

The results of the CR are shown in Table 8. The A0 has two boarding streamlines and one alighting streamline at one door, and A1–A4 have two boarding streamlines or two alighting streamlines. As alighting and boarding are separated, the conflicts between them are decreased to 0. From the results of Table 8, separating alighting and boarding substantially reduces bidirectional conflicts and the risk of virus infection during passenger flows in subways.

3.9. Discussion

With the low passenger flows during the severe COVID-19 pandemic, contrary to the current passenger organization scheme of alighting and boarding passenger flows sharing the same carriage doors, passengers are required to board or alight the train separately. Such an approach yields the promising outcome presented in Figs. 5–9 and Tables 3–6:

(1) The speed of separated passenger flows is elevated. Accordingly, conflicts are reduced to some degree. In other words, a fluent passenger flow is guaranteed, to further reduce the risk of COVID-19 virus infections among passengers.
(2) The density tapers off to relieve delays and conflicts between alighting and boarding passenger flows, despite an increased time of approximately 10%.

It is seen from Figs. 5–9 and Tables 3–6 that significant differences are not detected in the speed and density but do exist in time and distance. It is speculated that more time or distance to reach the carriage doors is needed if A4 (boarding at the second and third doors from the left and vice versa) is accepted. However, better speed and density indicators related to A4 over present schemes are observed. Furthermore, the results in Fig. 10 indicate an improved LOS for boarding flows in A4 compared with the other three alternatives, which implies passengers may walk more fluently with a better mood if they board at the second and third doors from the left. Tables 7 and 8 suggest that separated alighting and boarding can noticeably reduce conflicts at the subway carriage doors.

In this study, the separation of alighting and boarding focuses on how to effectively alleviate conflicts and adjacent contact in passenger flow processes and provides important prevention and control measures for pandemics in the platform queuing area. On the one hand, the high-density flow that was aggregated in a short time was reduced significantly and efficiently due to the shorter alighting and boarding times and better efficiency of the separation strategies, which abates conflicts and drives down infection risks. On the other hand, similar advantages of orderly alighting for passengers in the trains were also obtained, which was significant and yields a promising outcome in the diminishment of passenger conflicts in alighting and boarding, especially during special periods. For example, compared with existing schemes, the proposed schemes improved the speed and LOS, lowered the density, and reduced the conflicts and LOI. In addition, the separation strategies allowed passengers to move towards the doors in a more orderly manner, which mitigated in-carriage conflicts to some extent to further alleviate conflicts overall and reduce passenger contact [22].

Therefore, under the COVID-19 pandemic and lows passenger flow on subway platforms, the separated alighting and boarding schemes for safe travels are conducive to subway traveling and ensure a better environment in the station. As the spatiotemporal characteristics of subway passenger flows are considered, under abnormal situations, properly separating schemes (A1–A4) should be implemented based on the location and passenger flows in various subway stations at different times of the day. Otherwise, passenger comforts and transportation efficiency will be greatly affected.

4. Conclusions

Based on the characteristics of low passenger flows and high virus transmission risks during the COVID-19 pandemic in subway stations, this paper proposes separated alighting and boarding alternatives at subway stations to reduce the risk of viral infection. For the CA simulations implemented in Legion Studio, the separating scheme is a practical and effective approach to ensure safe and efficient subway operations, by decreasing conflicts, diminishing passenger densities, and lowering the risk of viral transmission. Moreover, among the four considered separation schemes, A4 is the most effective. However, the other separating schemes can also be applied accordingly.

The different schemes of passenger flow organization and validated alternatives that can decrease conflicts are compared with the current situation. In the future, the volume of passengers in the carriage and their behaviors after alighting and boarding will be considered together with various levels of impact factors in the model. Furthermore, this study is limited by the absence of general proximity, which will be considered in-depth in the future. A further study could assess different flows under different situations such as the districts with different emergency response levels and separated flow issues using passenger movements within the internal carriage as an example.

CRediT authorship contribution statement

Lishan Sun: Supervision, Methodology. Guang Yuan: Investigation, Software, Writing – original draft. Liya Yao: Conceptualization, Visualization, Writing – review & editing. Li Cui: Software, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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