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A Fuzzy-Theory-Based Social Force Model for Studying the Impact of Alighting Area Width on Alighting and Boarding Behaviors

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ABSTRACT Alighting and boarding efficiency (A&Be) of passengers plays an important role in the formulation of subway timetable. This paper studies the impact of alighting area width on A&Be based on the improved social force model. This improved model adopts the fuzzy logic theory considering factors of train dwell time and passengers ahead to determine the desired speeds of passengers instead of setting fixed values. The t-test method verifies the validity of the model. The passenger movement dynamics characterized by the alighted or boarded passenger quantities, the desired speeds, and the actual speeds over time is then analyzed. The simulation results indicate when people keep to the civilized rules of alighting first, A&Be will be improved significantly with increasing the alighting area width. Otherwise, the arbitrary increase of alighting area width does not necessarily improve A&Be. The alighting area width during the actual design should be determined by the specific passenger volume and passenger civility. Whether the countermeasure of adding the fences to separate the alighting passengers from the boarding passengers is effective to improve the travel efficiency is finally explored through analyzing the simulation results. Our findings could provide theoretical supports for decision-making of waiting area division on the subway platform and passenger flow management in reality.

INDEX TERMS Social force model, alighting area width, alighting and boarding efficiency, fuzzy logic theory.

I. INTRODUCTION

With the high accessibility and wide coverage, subway is gradually popular with the public. It plays an increasingly important role in our daily travel life. Take the mainland of China as an example, 37 cities have already operated urban rail transit whose total line length is up to 6126.82 km according to the statistical results before June 30, 2019 [1]. Train scheduling is very important to the efficient operation of the whole subway system, and the dwell time of train at each station directly affects the scheduling. When the dwell time is too short, passengers may have not enough time to alight and board. On the contrary, when the dwell time is too long, it will lead to unnecessary waste of time. Generally, passengers' alighting and boarding efficiency (A&Be) is closely related to the dwell time. Therefore, it is very necessary to study the influence factors that may affect A&Be.

Usually, passengers' A&Be has close relationships with whether there are platform edge doors or not, seat types, the widths of the carriage doors, and the height between train and platform [2], [3]. De Ana Rodríguez *et al.* [4] concluded that A&Be was not related to the width of the platform edge door. Holloway *et al.* [5] found that the process of alighting and boarding (A&B) for young passengers was almost unaffected by the type of luggage, while the corresponding behaviors of elderly people were affected. In addition, the effects of some other factors, such as the degree of congestion on the subway platform, the interaction between passengers and dispatchers, the waiting area types, boarding strategies, and the time gap between the first alighting passenger and the first

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boarding passenger, on A&Be were deeply studied in [6]–[9].

The existing studies on different factors affecting passengers' A&Be provide some theoretical suggestions for the design of carriage, the command of dispatchers, etc. However, literature research shows that there was no relevant research on the impact of alighting area width which differs on different subway platforms on passengers' A&Be. This paper, therefore, mainly focuses on this issue, which could help to put forward design suggestions of the waiting area divisions on the subway platform.

Pedestrian dynamics model provides a way of imitating the movements of A&B passengers. Usually, it can be divided into the macroscopic model and the microscopic model [10]–[12]. The macroscopic model, mainly referring to the fluid dynamics model, regards the pedestrian flow as a whole research object on the basis of the average crowd speed and density. The computational complexity is therefore relatively low especially for the large-scale crowd movement simulation. However, the macroscopic model cannot take individual interactions into account, which is not suitable for our investigation purposes. The microscopic model fully considers the heterogeneity of each pedestrian, and could simulate the interactions among pedestrians. We, therefore, choose a microscopic model as a basic driven model of passengers in this paper.

The microscopic model mainly includes the social force model (SFM), the cellular automata model, and the game theory model [8]. The SFM [13]–[15] is a spatiotemporal continuous model based on Newton's second law, which fully considers the individual willingness, the interactions among pedestrians and the interactions between the pedestrian and surrounding obstacles. The SFM has been constantly improved to meet new requirements, including introducing the real video data and the mental state [16]. The cellular automata model [17]–[20] belongs to a spatial discrete model, and pedestrians in the cellular world decide to choose which cellular in the next step according to their maximum motion probability. Lattice gas model [21]–[23] is a special cellular automata model. The game theory model [24]–[26] is usually developed based on the game theory to solve the conflicts of pedestrians.

In this paper, we choose the microscopic SFM as the basic movement model of passengers. One main reason is that the SFM could well represent some self-organization behaviors of passengers, such as the spontaneous lane formation of the counter A&B passenger flow, and the arching effect around the carriage door in the train [27], [28]. Another important reason is that the SFM could fully take the psychological factors of passengers such as impatience and panic into considerations [29]. More over, the freedom of pedestrian motion when using the discrete model represented by the cellular automata model is limited because of discrete mesh.

The rest of this paper is organized as follows. Section III updates the desired speeds of passengers in the SFM based on the fuzzy logic theory, which considers the train dwell time and passenger quantity ahead with the purpose of A&B. Section IV verifies the improved model, and further analyzes passenger movement dynamics and efficiency under different civilizations of passengers and different alighting area widths based on the simulation results. Moreover, the countermeasure of adding the fences on the platform is also investigated. Section V concludes the main results of this paper.

II. DESIGN OF ALIGHTING AREA WIDTH ON THE SUBWAY PLATFORM

According to our field investigations of the waiting area types on the subway platform, there are two types of waiting areas. The first type is with double-boarding area and single-alighting area that is what we often see when taking subway as shown in FIGURE 1. The second type is with single-boarding area and single-alighting area that could be observed in some hub stations such as Qingdao Wusi square subway station, China. The findings in [8] indicate that the frequently used first type of design is more conducive to passenger traffic of A&B. This paper, therefore, mainly focuses on the first waiting area type in order to find out more factors that may affect A&Be. Note that A&Be in this paper is characterized by the total time of A&B.

Through our field observations of the subway platform in some cities such as Beijing, Guangzhou and Hong Kong, an interesting phenomenon was found that the alighting area width in some stations was different as shown in FIGURE 1. Obviously, the ratios of the alighting area width to the carriage door width in FIGURES 1(a), 1(b), and 1(c) are about 1/4, 1/2, 1, respectively. This phenomenon stimulates our desire to study this issue. We, therefore, choose the alighting area width as an important factor to explore A&Be.

III. MODEL

A. THE INTRODUCTION OF THE SFM

The movements of A&B passengers in this paper are driven by the SFM [30]. In the SFM, the motion equation is built as given in Eqs. (1)-(4).

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_w \vec{f}_{iw}. \tag{1}$$

$$\vec{f}_i^0 = m_i \frac{v_i^0(t)\,\vec{e}_i^0 - \vec{v}_i(t)}{\tau_i}. \tag{2}$$

$$\begin{aligned}\vec{f}_{ij} &= A_i \exp\left[\left(r_{ij} - d_{ij}\right)/B_i\right] \vec{n}_{ij}(\lambda_i + (1-\lambda_i) \\ &\quad \times \frac{1+\cos(\varphi_{ij})}{2}) + kg\left(r_{ij} - d_{ij}\right)\vec{n}_{ij} \\ &\quad + \kappa g\left(r_{ij} - d_{ij}\right)\Delta v_{ji}^t \vec{t}_{ij}.\end{aligned} \tag{3}$$

$$\begin{aligned}\vec{f}_{iw} &= A_i \exp[(r_i - d_{iw})/B_i]\vec{n}_{iw} + kg(r_i - d_{iw})\vec{n}_{iw} \\ &\quad + \kappa g(r_i - d_{iw})\Delta v_{wi}^t \vec{t}_{iw}.\end{aligned} \tag{4}$$

$$g(x) = \begin{cases} 0 & \text{if } d_{ij} > r_{ij} \\ x & \text{if } d_{ij} \leqslant r_{ij} \end{cases} \tag{5}$$

The acceleration of passengers is influenced by three forces in the right side of the equal sign of the master Eq. (1). The first term $\vec{f}_i^0$ indicates the desired force, the second term

(a) Type A_1.

(b) Type A_2.

(c) Type A_3.

FIGURE 1. Three types of alighting area width on the subway platform.

$\vec{f_{ij}}$ indicates the individual interactive force among passengers, and the third term $\vec{f_{iw}}$ indicates the interactive force between passengers and surrounding obstacles.

The definitions of specific parameters in Eqs. (1)-(4) are listed in Table 1.

B. A FUZZY-THEORY-BASED METHOD FOR MODELING PASSENGERS' DESIRED SPEEDS

According to [31], [32], the desired velocity, namely the desired speed and the desired direction, has a great impact on traffic efficiency of pedestrians. A method for determining the desired velocity of A&B passengers was given in [8]. Among which, the definition of desired speed takes full account of the train dwell time, and the desired direction is defined to point to a certain point which is set through dividing the cross section of the carriage door into multiple segments [8].

In this paper, the same fine partition method as given in [8] is used to define the desired directions of A&B passengers. Generally, the desired speeds of passengers could be affected by many factors such as dwell time, surrounding people and environment. However, these factors integrated into the desired speed usually cannot be precisely defined. Fuzzy logic theory due to its unique advantage of strong robustness is introduced in this paper to investigate the definition of desired speeds of passengers, which could show advantages over the precise definition method in [8].

Traditional mappings usually contain two values, that is, 0 and 1. When element A belongs to a set, it is 1; otherwise, it is 0. This traditional mapping method only applies to exact correspondence. In real life, there are many relationships that cannot be accurately measured. The fuzzy logic theory, however, could fill this gap very well. It is a mathematical modeling method based on fuzzy sets and the related membership functions. The commonly used membership functions usually include several typical distributions such as Gaussian, triangular, bell, trapezium membership functions. Note that the range of membership function belongs to [0,1]. When the value of membership function is 1, it means the complete membership. When the value of membership function is 0, it means the complete lack of membership [33].

The process of fuzzy logic theory generally includes four steps: Fuzzification, the rule base, the inference engine and defuzzification.

Fuzzification refers to transforming the clear values of input variables into the corresponding fuzzy values based on the membership functions of fuzzy sets. Two key parameters are adopted as input variables of fuzzy inference system to determine the desired speed, namely the time that has elapsed during dwell time t^p_{dwell} also used in [8] and passengers ahead with the purpose of A&B whose quantity is marked as N_{ahead}.

t^p_{dwell} could affect the psychological state of passengers obviously, its states in this paper are expressed by a fuzzy set $\{S_t, M_t, L_t\}$. Note that "S_t", "M_t", "L_t" respectively represent the values of t^p_{dwell} are small, medium and large. For example, when the train just arrives at the station which means the value of t^p_{dwell} is small, passengers on the platform would think that there is enough time to get on the train. At this time, they are not in a hurry, and the state of t^p_{dwell} for these people is defined as "S_t". Statistical results show that the dwell time in different subway stations is different which is usually between 30 s and 40 s [34]. This paper specially sets the dwell time to be 35 s during our study. The corresponding membership functions for t^p_{dwell} are expressed by Eq. (6) shown in FIGURE 2.

$$\mu(t^p_{dwell}) = \begin{cases} e^{-\frac{(t^p_{dwell}+6)^2)}{200}}, & 0 \leqslant t^p_{dwell} \leqslant 35. \\ e^{-\frac{(t^p_{dwell}-17.5)^2}{112.5}}, & 0 \leqslant t^p_{dwell} \leqslant 35. \\ e^{-\frac{(t^p_{dwell}-41)^2}{200}}, & 0 \leqslant t^p_{dwell} \leqslant 35. \end{cases} \tag{6}$$

To a certain extent, N_{ahead} could also affect the psychological state of passengers, its states are expressed by a fuzzy set $\{S_n, M_n, L_n\}$. It is worth noting that "S_n", "M_n", "L_n" represent the values of N_{ahead} for the current passenger are small,

TABLE 1. The definitions of specific parameters in the SFM [30].

Symbol	Definition
i, j	Pedestrians
w	Surrounding obstacles
m_i	The mass of passenger i
$\vec{v}_i(t)$	The velocity of passenger i at time t
v_i^0	The desired speed of passenger i
$\vec{e}_i^0$	The desired direction of passenger i
τ_i	The reaction time of passenger i
A	The interaction strength
B	The magnitude of repulsive interaction
r_i	The radius of passenger i
r_{ij}	$r_{ij} = r_i + r_j$
d_{ij}	The Euclidean distance between pedestrians i and j
k	The coefficient of body compression
κ	The coefficient of sliding friction
$\vec{r}_i$	The location of passenger i
$\vec{n}_{ij}$	The normalized vector, $\vec{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\vec{r}_i - \vec{r}_j)/d_{ij}$
$\vec{t}_{ij}$	The tangential vector, $\vec{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$
$\triangle v_{ji}^t$	The velocity difference along the tangential direction, $\triangle v_{ji}^t = (\vec{v}_j - \vec{v}_i) \cdot \vec{t}_{ij}$
φ_{ij}	The visual angle, $\cos(\varphi_{ij}) = -\vec{n}_{ij} \cdot \vec{e}_i$
λ_i	The non-isotropic impact of the visibility, $0 \leq \lambda_i \leq 1$

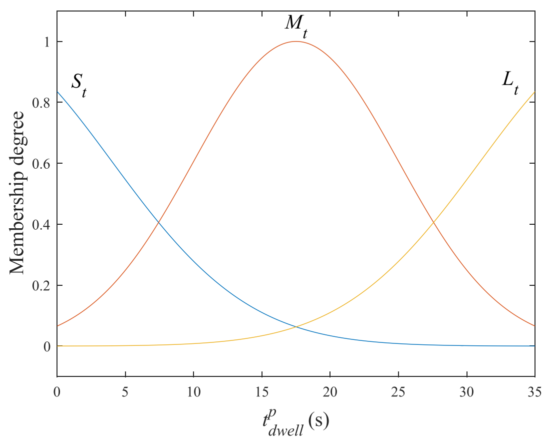


FIGURE 2. The membership function $\mu(t^p_{dwell})$ for input variable t^p_{dwell}.

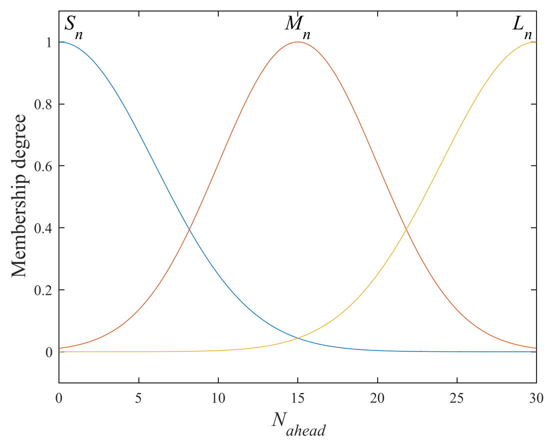


FIGURE 3. The membership function $\mu(N_{ahead})$ for input variable N_{ahead}.

medium, and large, respectively. If N_{ahead} is very large for the current passengers, they will get worried about whether they could get on or get off the train in time. At this time, the desired speeds may increase. We, therefore, define the state of N_{ahead} as "L_n". Similarly, we define the states "S_n", "M_n" for N_{ahead}. The corresponding membership functions for N_{ahead} are given by Eq. (7) shown in FIGURE 3.

$$\mu(N_{ahead}) = \begin{cases} e^{-\frac{N_{ahead}^2}{72}}, & 0 \leqslant N_{ahead} \leqslant 30. \\ e^{-\frac{(N_{ahead}-15)^2}{50}}, & 0 \leqslant N_{ahead} \leqslant 30. \\ e^{-\frac{(N_{ahead}-30)^2}{72}}, & 0 \leqslant N_{ahead} \leqslant 30. \end{cases} \quad (7)$$

After setting up the membership functions, the states for t^p_{dwell} and N_{ahead} could be determined according to the specific input values of t^p_{dwell} and N_{ahead}. Then, the *if − then* rules are needed to perform the inference process of determining the desired speed. The fuzzy natural language is used to express the rules listed in Table 2. Note that the rules

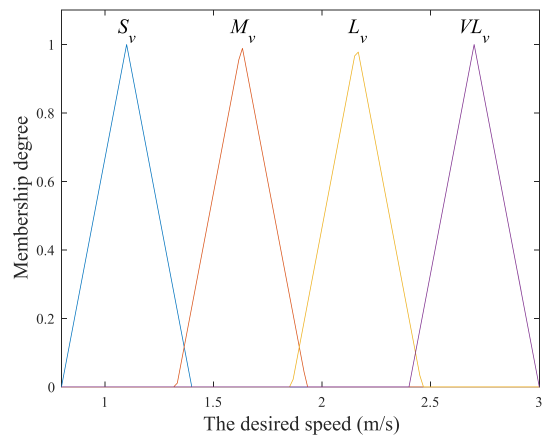


FIGURE 4. The membership function $\mu(v_i^0)$ for the output variable of the desired speed v_i^0.

in Table 2 are set according to our limited travel experience and knowledge. The states of output value of the desired speed in the developed fuzzy inference system are expressed

TABLE 2. The inference rules of determining the desired speeds.

Rule number	Fuzzy rules
Rule 1	if t^p_{dwell} is S_t and N_{ahead} is S_n, then the desired speed is S_v
Rule 2	if t^p_{dwell} is S_t and N_{ahead} is M_n, then the desired speed is M_v
Rule 3	if t^p_{dwell} is S_t and N_{ahead} is L_n, then the desired speed is L_v
Rule 4	if t^p_{dwell} is M_t and N_{ahead} is S_n, then the desired speed is S_v
Rule 5	if t^p_{dwell} is M_t and N_{ahead} is M_n, then the desired speed is L_v
Rule 6	if t^p_{dwell} is M_t and N_{ahead} is L_n, then the desired speed is L_v
Rule 7	if t^p_{dwell} is L_t and N_{ahead} is S_n, then the desired speed is M_v
Rule 8	if t^p_{dwell} is L_t and N_{ahead} is M_n, then the desired speed is L_v
Rule 9	if t^p_{dwell} is L_t and N_{ahead} is L_n, then the desired speed is VL_v

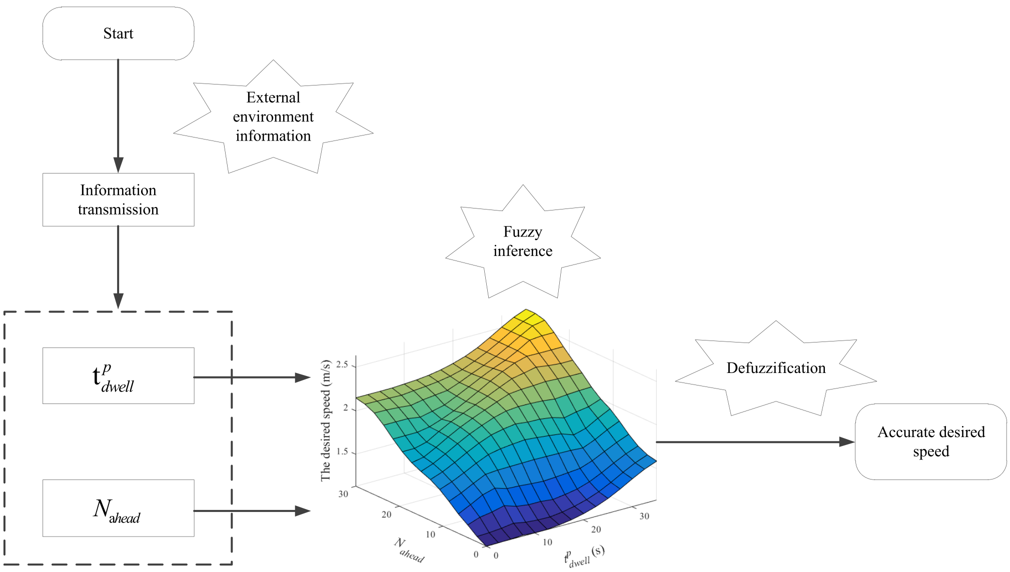


FIGURE 5. The Mamdani fuzzy logic system for determining the desired speed.

by a set $\{S_v, M_v, L_v, VL_v\}$ illustrated in FIGURE 4 and determined by Eq. (8). "S_v", "M_v", "L_v", "VL_v" denote that passengers are with the small value, medium value, large value, and very large value of desired speeds, respectively. This paper adopts the typical Mamdani fuzzy inference method [35], [36] to realize the fuzzy implication.

$$\mu(v_i^0)=\begin{cases} max(min(\frac{10v_i^0-8}{3}, \frac{14-10v_i^0}{3}), 0), & 0 \leqslant v_i^0 \leqslant 3. \\ max(min(\frac{100v_i^0-133}{30}, \frac{193-100v_i^0}{30}), 0), & 0 \leqslant v_i^0 \leqslant 3. \\ max(min(\frac{50v_i^0-93}{15}, \frac{123-50v_i^0}{15}), 0), & 0 \leqslant v_i^0 \leqslant 3. \\ max(min(\frac{10v_i^0-24}{3}, \frac{30-10v_i^0}{3}), 0), & 0 \leqslant v_i^0 \leqslant 3. \end{cases} \quad (8)$$

The typical centroid defuzzification method is adopted in this paper to obtain an accurate result of the desired speed. Therefore, the Mamdani fuzzy logic system for determining the desired speed is developed as shown in FIGURE 5. Note that the desired speeds of passengers will conform to the normal distribution with the mean value 1.34 m/s, once they complete the alighting or the boarding behavior. Furthermore, if the time left in the dwell time is less than 5 s, the desired speeds of passengers who have not alighted or boarded will deliberately set to be the maximum value which is 2.01 m/s.

IV. SIMULATION

During the actual management of the A&B passenger flow in the subway stations, the alighting first regulation is always recommended which is transmitted through the radio or the publicity. However, it's difficult to achieve such civilized behaviour, especially during the morning and evening rush hours. Here, we specially mark the passenger quantity who have alighted as NN_a, and the passenger quantities who have boarded from the left and the right waiting areas as NN_b^l and NN_b^r. Mark initial total numbers of A&B passengers as N_a and N_b, respectively. Therefore, this paper introduces γ to indicate the proportion of NN_a to N_a. We assume that when γ reaches the set value, the passengers will begin to board.

In this section, we first verify the proposed modelling method in this paper based on t-test method. Then, passenger movement dynamics on the basis of the simulation results under the situations of $\gamma = 0.1$ and $\gamma = 1$ is analyzed. Moreover, passengers' A&Be under different values

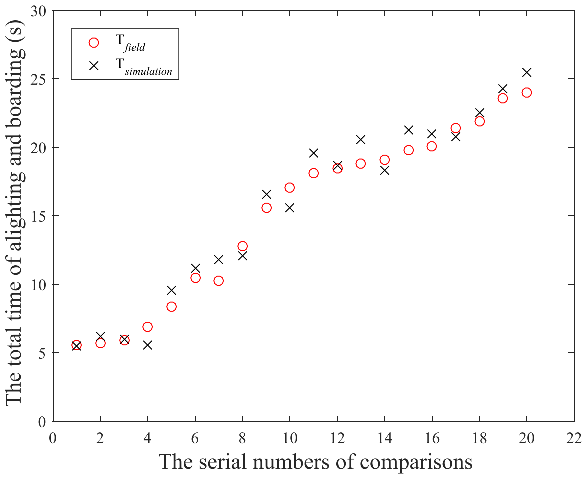


FIGURE 6. The comparison results of T_t between the field data and the simulation data.

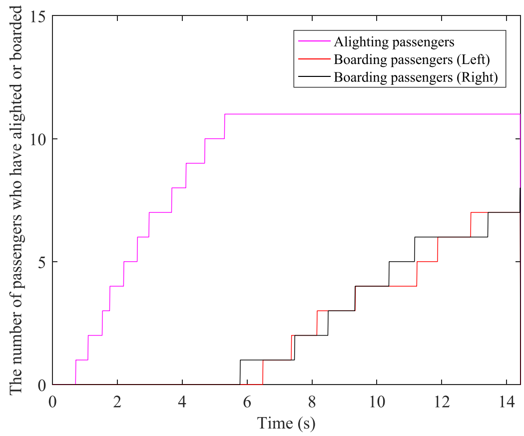
of the alighting area width is explored through comparing the simulation results. Finally, the countermeasure of adding the fences on the subway platform is analyzed.

A. MODEL VERIFICATION

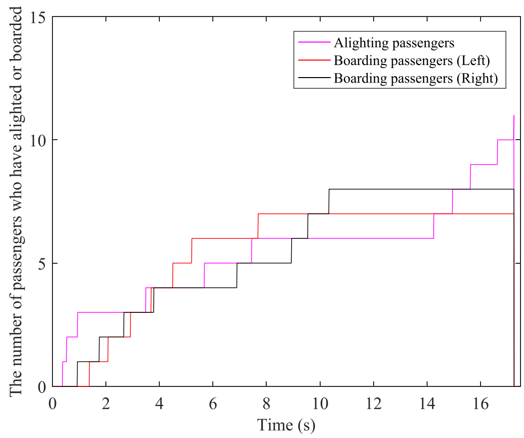
The work of model verification is very important. It can show whether the model can truly reflect the actual A&B behavior to some extent. In this paper, the same model verification method in [8], [37] is adopted based on t-test method. It is worth noting that when obtaining the simulation results, N_a, N_b and the moment that triggers the boarding behavior will keep the same with those collected in the field investigations.

FIGURE 6 shows 20 times comparison results of the total time T_t between the field data T_{field} and the simulation data $T_{simulation}$ in the A&B process. Note that the field data is collected from the subway station in Qingdao, China, which keeps the same with that in [8]. It can be obtained by t-test that the calculated t value is -0.1639, and t-critical value is 2.093 under the confidence level of 95%. It means $t < t_{0.05/2,19}$, which indicates that there is no difference between the simulation results and the field data in a statistical sense. Therefore, the proposed modeling method in this paper can be used to study passengers' A&Be.

Although both the proposed fuzzy-theory-based method and the precise definition method in [8] for modelling the desired speed are effective according to t-test results, the method in this paper which utilizes the advantages of data information, human-simulated fuzzy reasoning ability and low computational complexity could deal well with the opposition between complexity and accuracy without the requirement of establishing an exact mathematical model. This paper only provides a method for defining the desired speed. The accuracy of the model can be further achieved by controlling input variables, membership functions, rule base and other factors.



(a) γ=1.



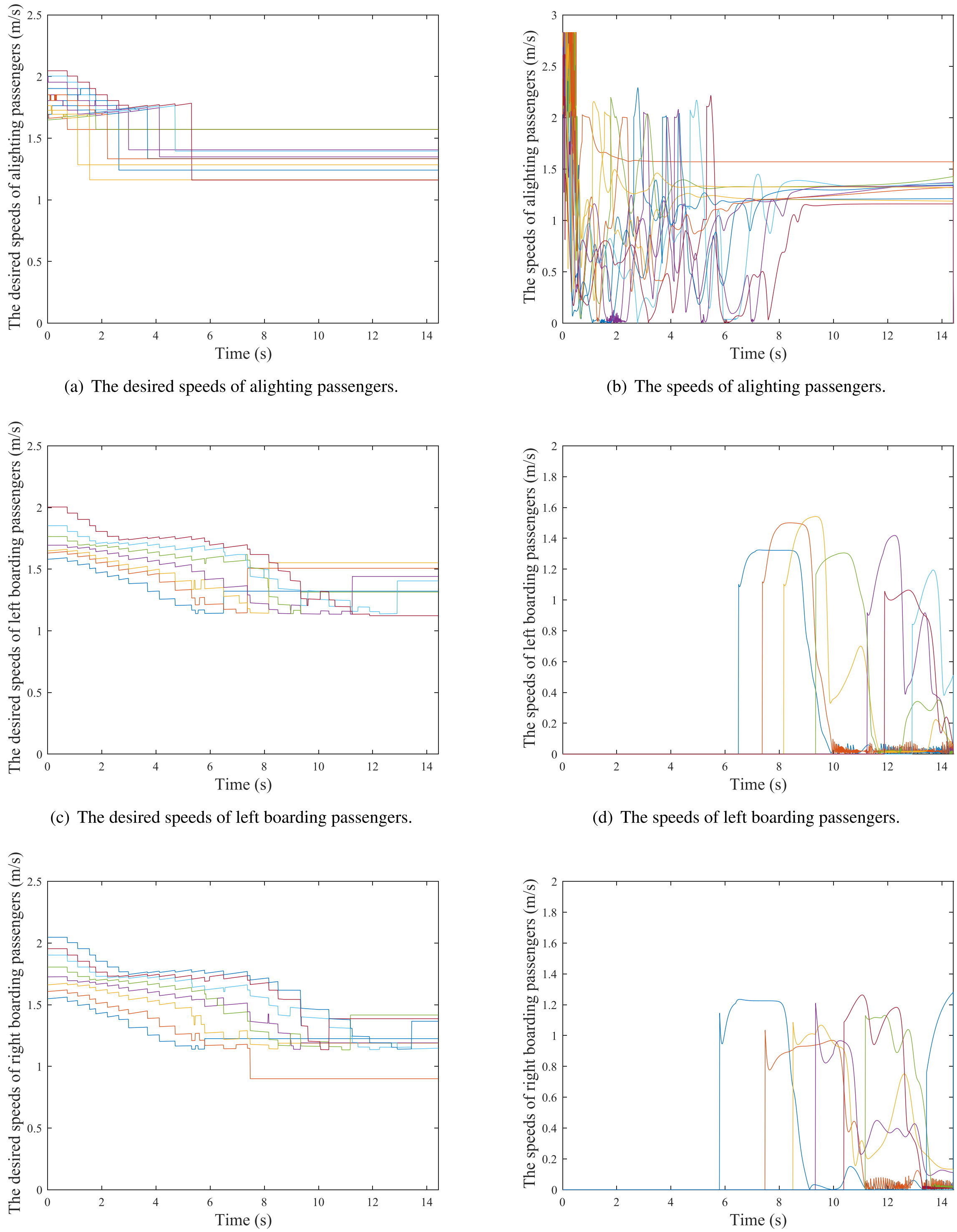
(b) γ=0.1.

FIGURE 7. NN_a, NN_b^l and NN_b^r versus time.

B. THE ANALYSIS OF THE PASSENGER MOVEMENT DYNAMICS

This section mainly focuses on analyzing the passenger movement dynamics characterized by NN_a, NN_b^l, NN_b^r, the desired speeds, and the actual speeds as time goes on. Specially, it is assumed that N_a is 11, N_b is 15, and the alighting area width W_a is 1 m. Note that the initial boarding passengers in waiting areas on both sides are evenly allocated according to the distribution method proposed in [38].

FIGURE 7 shows the variations of NN_a, NN_b^l and NN_b^r over time, when $\gamma = 1$ and $\gamma = 0.1$, respectively. In the situation of $\gamma = 1$, the value of NN_a increases steadily over time until NN_a reaches N_a around 5 s. Then, the boarding behavior is triggered after all of the passengers have got off the train. In the process of the whole A&B, there is almost no competition conflict for the carriage door between the alighting passenger flow and the boarding flow. However, the increases in values of NN_a, NN_b^l and NN_b^r occur simultaneously during some time periods in FIGURE 7(b), which indicates that there are inevitably scrambles for the carriage door among passengers when $\gamma = 0.1$. Meanwhile,



(a) The desired speeds of alighting passengers.

(b) The speeds of alighting passengers.

(c) The desired speeds of left boarding passengers.

(d) The speeds of left boarding passengers.

(e) The desired speeds of right boarding passengers.

(f) The speeds of right boarding passengers.

FIGURE 8. The desired speeds and actual speeds of passengers versus time when $\gamma = 1$.

we could find that some passengers who want to get off are stuck in the carriage during the time period [7 s, 14 s] until passengers who have boarded around the carriage door make room for them. Through the comparative analysis of FIGURES 7(a) and 7(b), it can be found that T_t when $\gamma = 1$ is less than that when $\gamma = 0.1$. This conclusion is consistent with our daily travel experience and the simulation result in [8]. Further more, the values of T_t when $\gamma = 1$ and

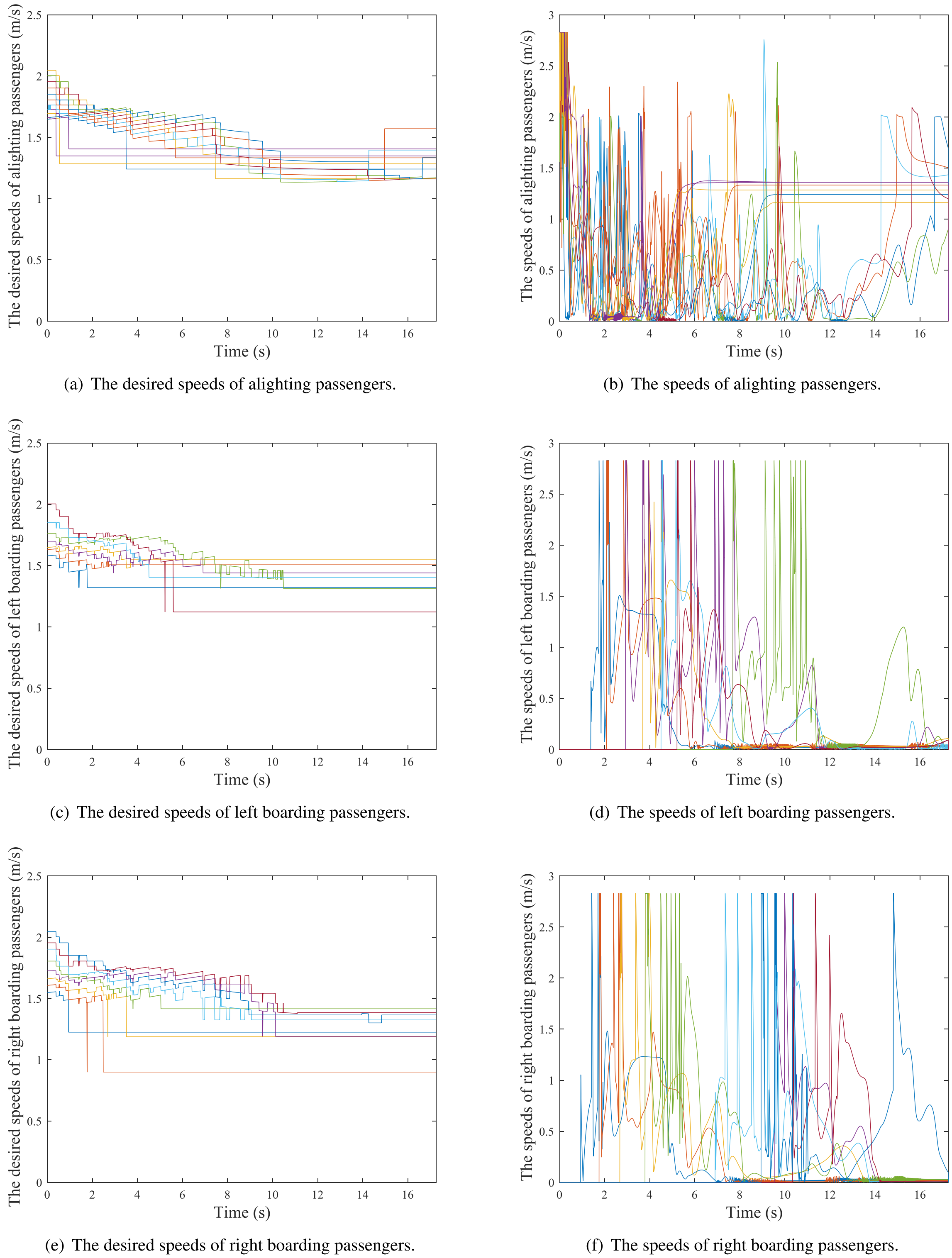
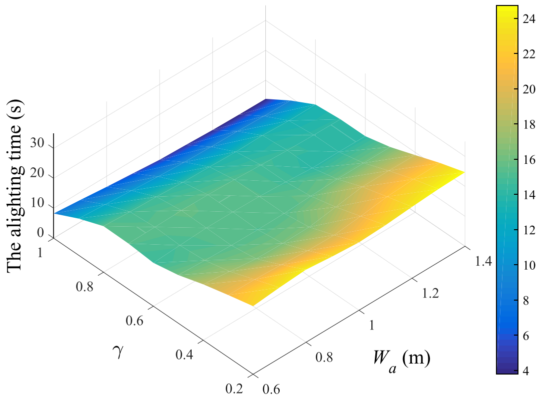


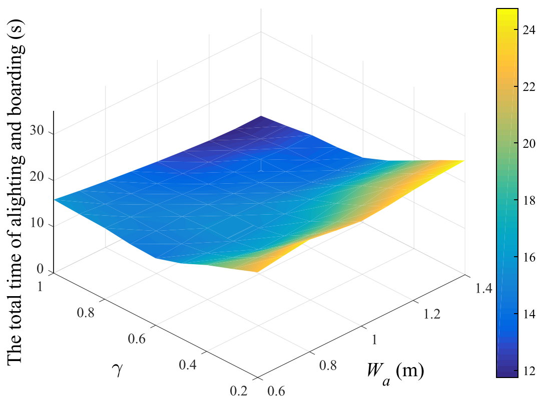
FIGURE 9. **The desired speeds and actual speeds of passengers versus time when $\gamma = 0.1$.**

$\gamma = 0.1$ are within the ranges of the simulation results in [8], which further indicates the feasibility of the definition method for the desired speed based on the fuzzy logic method.

FIGURE 8 shows the variations of desired speeds and actual speeds of passengers over time when $\gamma = 1$. In the initial time period [0 s, 3 s] which means t^{p}_{dwell} is small, the desired speeds of alighting passengers in FIGURE 8(a)

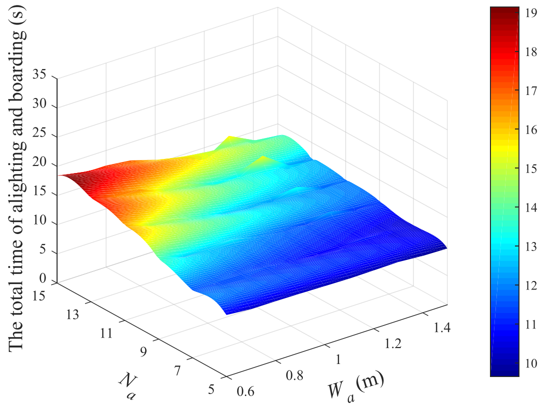


(a) The alighting time versus γ and W_a.

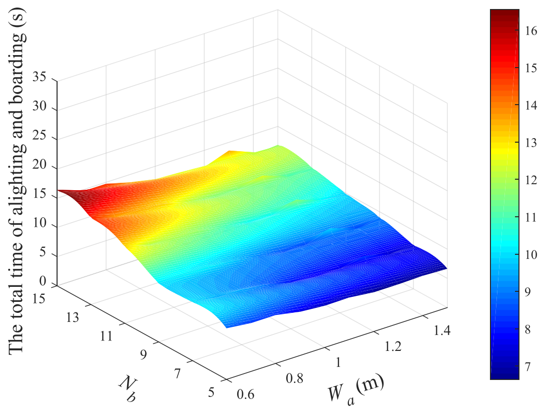


(b) T_t versus γ and W_a.

FIGURE 10. **The travel efficiency of passengers versus γ and W_a.**



(a) T_t versus N_a and W_a.



(b) T_t versus N_b and W_a.

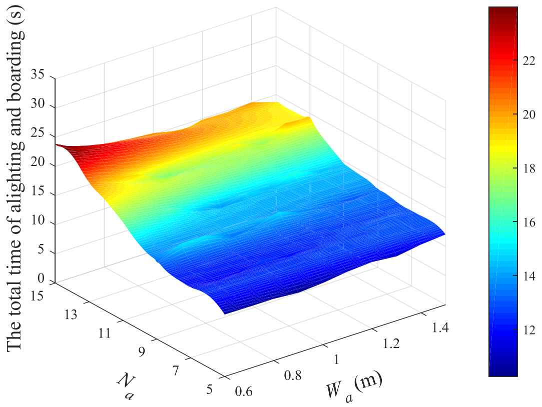
FIGURE 11. **The variation of T_t when $\gamma = 1$.**

decrease over time because of the reduction of the dominant factor N_{ahead}. The desired speeds of the left four passengers who are still in the carriage begin to increase with increasing t^p_{dwell}. In FIGURE 8(b), there is a certain fluctuation in the actual speed of alighting passenger which is determined by the corresponding desired speed and the surrounding passengers and environment. We can observe the stop-and-go passenger flow which is in line with our daily travel rules. After all of alighting passengers get off the train, passengers begin to board around 6 s reflected from FIGURES 8(d) and 8(f). Note that even though we have been calculating the desired speed of the boarding passenger in FIGURES 8(c) and 8(e) based on the proposed method in section III-B, the movements of boarding passengers could not be trigged until the proportion of passengers who have got off reaches γ. For the boarding passengers, their corresponding values of N_{ahead} no longer include the alighting passenger quantity when $\gamma = 1$. Thus, N_{ahead} is not very large which could lead to the reduction of the desired speeds when t^p_{dwell} is also not very large.

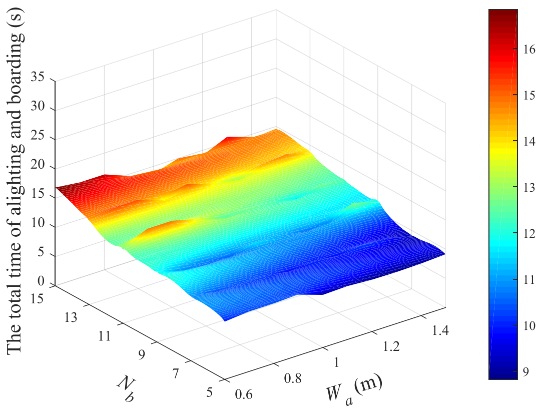
FIGURE 9 shows the desired speeds and the actual speeds of passengers over time when $\gamma = 0.1$. When two passengers get off the train, the waiting passengers will begin to board at about 1 s. Thereby, the counter passenger flow could be formed for a period of time reflected from FIGURES 9(b), 9(d) and 9(f). Combining the results in FIGURE 7(b), we can see from FIGURE 9(b) that once the boarding behavior completes, the last few people left in the carriage waiting to get off will quickly increase their walking speeds which is the result of the increase of their desired speeds in FIGURE 9(a) in order to complete the alighting behavior as soon as possible. Moreover, we could find that passengers' speeds can reach the maximum set instantaneously, because there are a lot of competitions and conflicts between the opposite passengers in the time period about [2 s, 11 s]. It is worth noting that the speeds of passengers who have got on the train will become very small which are around about 0.1 m/s or even be 0 once they arrive at their destinations.

C. TRAVEL EFFICIENCY ANALYSIS OF ALIGHTING AND BOARDING UNDER DIFFERENT W_A IN THE CASE OF $0 \leq \gamma \leq 1$

In this section, A&Be versus γ and W_a is first studied as shown in FIGURE 10. Note that $N_a = 11$ and $N_b = 15$.



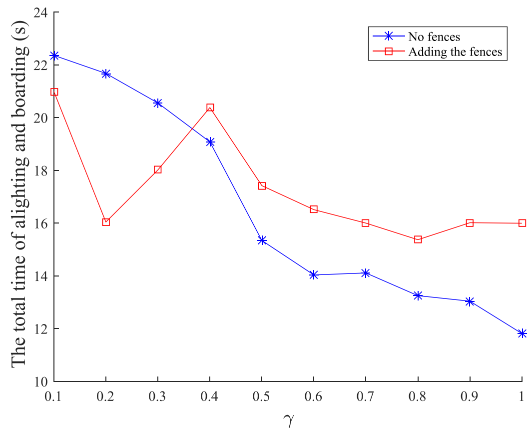
(a) T_t versus N_a and W_a.



(b) T_t versus N_b and W_a.

FIGURE 12. The variation of T_t when $\gamma = 0.5$.

(a) Add the fences in reality.



(b) The travel efficiency analysis.

FIGURE 13. The countermeasure adopted on the subway platform.

FIGURE 10 reflects that both the alighting time and T_t increase when γ gets closer and closer to 0. When γ is close to 1, we can find the decrease trend of T_t with increasing W_a. However, this decrease trend could not be observed when γ gets closer to 0. In order to comprehend the impact of W_a on A&Be deeply, T_t versus N_a and N_b under different W_a is further studied as shown in FIGURES 11 and 12 when $\gamma = 1$ and $\gamma = 0.5$, respectively.

Both FIGURES 11 and 12 indicate that when the alighting area width W_a is determined, T_t will increase with increasing N_a or N_b in the cases of $\gamma = 1$ and $\gamma = 0.5$, respectively. Among which, $N_b = 15$ in FIGURES 11(a) and 12(a), and $N_a = 11$ in FIGURES 11(b) and 12(b). Moreover, when N_a in FIGURE 11(a) or N_b in Figure 11(b) is determined, T_t will decrease with increasing W_a. This conclusion is consistent with that obtained from FIGURE 10(b). However, the variation trend of T_t with increasing W_a in the case of $\gamma = 0.5$ is different under different fixed N_a in FIGURE 12(a). When the fixed N_a is relative large such as $N_a = 15$, T_t does decrease with increasing W_a. Nevertheless, T_t will increase with increasing W_a when N_a is relative small such as $N_a = 5$. The reason for this is that the larger alighting space is wasted due to the small N_a in the case of $\gamma = 0.5$.

By comparing the color changes in FIGURES 11 and 12 especially when the fixed N_a or N_b is relative large, we can conclude that the alighting area width in the case of $\gamma = 1$ has a greater impact on T_t than that in the case of $\gamma = 0.5$. In brief, when alighting first is executed, A&Be will indeed be improved through increasing the alighting area width. However, when $0 \leq \gamma < 1$, blindly increasing the alighting area width does not necessarily improve travel efficiency. At this time, W_a should be determined according to the values of N_a and N_b. In the actual passenger flow management process, each subway station should set the alighting area width according to the specific passenger volume and passenger civility.

D. COUNTERMEASURE ANALYSIS

According to our field investigations, some stations usually take relevant measures in order to improve A&Be such as adding the fences shown in FIGURE 13(a). Note that FIGURE 13(a) was photographed in the subway station of Guangzhou, China. Can this countermeasure really improve travel efficiency by separating the boarding passengers from alighting passengers? Indeed, this countermeasure could definitely decrease the conflicts between the counter flows when $0 \leq \gamma < 1$. We expect to illustrate whether this is reasonable by simulation results.

The simulation experiments are done in the scenario corresponding to that in FIGURE 13(a). Note that $W_a = 1.4$ m as an example, $N_a = 11$, and $N_b = 15$. FIGURE 13(b) shows the comparison results of the median values of T_t. Simulation data indicates that adding the fences could reduce T_t when γ is relatively small. This is because the fences could reduce the conflicts of the counter flow once trigging the boarding behaviors. However, when the value of γ continuously increases such as $\gamma > 0.4$, the fences could not improve the travel efficiency because of the waste space resulting from the existence of fences. This conclusion is especially obvious when $\gamma = 1$. The A&B passengers do not compete for doors in the case of $\gamma = 1$, and the existence of fences only leads to the reduced walking space. Therefore, whether or not needing the fences in reality depends much on γ. When passengers fully keep to the civilized rule, the fences are not necessary as expected.

V. CONCLUSION

In this paper, the fuzzy logic theory, fully taking the advantages of data information, human-simulated fuzzy reasoning ability and low computational complexity, is introduced into the SFM to determine the desired speed of passengers. Among which, t^p_{dwell} and N_{ahead} are taken as input variables of fuzzy inference system. The t-test method is used to explain the feasibility of the improved model which can continue to be more precise according to actual requirements. The simulation results indicate that T_t tends to increase with the decrease of γ. When the alighting area width is determined, T_t will increase as N_a or N_b increases. Only under the premise of keeping to the regulation of alighting first, can T_t be shortened obviously by increasing the alighting area width. It indicates that the alighting area width should be designed according to the values of N_a, N_b and γ which can be collected by daily statistics of passenger flow. The necessity of fences in reality depends much on γ. When γ is relative small, it does need to add the fences. Otherwise, it is not necessary.

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