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Simulation-Based Optimization in a Bidirectional *A*/*B* Skip-Stop Bus Service

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ABSTRACT A two-way bus corridor system always suffers severe demand imbalance between their two operational directions during the peak hours. This paper intends to minimize the average passenger travel time by applying the *A*/*B* skip-stop strategy in such an imbalance situation. This strategy defined three types of stations: *A*, *B*, and *AB*. In the service, the buses depart alternately from the original station as type *A* and *B*, and *A* (or *B*) buses serve *A* (or *B*) stations, as well as *AB* stations. Then the problem becomes determining the skip-stop patterns for both directions. A heuristic genetic algorithm is adopted to solve this problem with a kernel of a precise simulation model depicting the bus system. Finally, we apply the optimization method to a realistic bus corridor of BRT line 1 in Beijing, China. Results demonstrate that the bidirectional *A*/*B* skip-stop service prevails over the unidirectional services applying *A*/*B* skip-stop only on one direction, and the common used regular service visiting all stations. It is certificated that the bidirectional skip-stop service reduces bus bunching, yields a more balanced bus load and provides a smooth bus service with lower cycle time and variability. Moreover, a sensitivity analysis is conducted to show the impacts of some key attributes on potential benefits of bidirectional skip-stop service. Finally, the elastic demand case where transferring passengers may change their origins or destinations has been discussed.

INDEX TERMS Bus operation, bus route model, service level, simulation-based optimization, transportation management.

I. INTRODUCTION

In many urban cities, especially in the peak hours, the existing bus transit system is inadequate to accommodate the huge travel demand. Once the travel time accompanying with the in-bus crowed exceed what is considered acceptable, the operator is expected to expand system capacity. However, increasing the transit investments, e.g., new buses or bus lines, is often expensive, which is not a sustainable and effective way for good transit serviceability. Alternatively, optimizing the transit operational strategies provides potential to improve the efficiency and reliability of transit systems. A variety of such control methods are provided, e.g., bus holding, skip-stop, signal priority, bus speed regulation, and a comprehensive classification of the studies is presented in the literature [1].

Here, we mainly focus on the skip-stop service, in which each bus visits only a fixed subset of the stations. This strategy improves service level by reducing user in-vehicle time and vehicle cycle time due to fewer stops of vehicles. Transit agencies implement skip-stop bus services as a mean to provide an attractive and competitive transit service by selecting suitable skip-stop services and determining which stations to skip. A number of previous studies have been conducted to design such services and most of them are applied to a single direction with unbalanced distribution of the passengers along the corridor, e.g., [2]–[7]. Some of the researchers noted the travel demand imbalance between the two operational directions, and they attempted to assign the available fleet by increasing the frequency on the most demanded route segments in order to adjust the demand to the effective capacity of buses [8]–[11]. Specially, there are two strategies being defined for specific bus line, (a) short turn service: some buses serving a line make shorter cycles in order to concentrate on areas of greater demand, e.g., [12], [13]; and (b) deadheading: empty vehicles return to the line starting point in the low-demand direction in order to begin another run as quickly as possible in the high-demand direction e.g., [14], [15]. Generally, the two strategies operate with other services, e.g., regular service. In this case, a skip-stop bus can easily catch up with and overtake a regular bus, which are not applicable for transit lines without overtaking lanes.

This work studies an alternative skip-stop service to improve the effectiveness of bus lines considering demand imbalance between operational directions. Encouraged by a successful implementation of a named *A*/*B* skip-stop express strategy in the railway system in Metro de Santiago [16], we try to transplant this strategy to the bus line system, for the similarities among the two systems. In such a strategy, stations are categorized as stations *A*, *B*, and *AB*. Vehicles depart in turn from the first station of a route as type *A* and *B*. *A* trains stop at *A* stations and *AB* stations, and *B* trains stop at *B* stations and *AB* stations (Vuchic [17], [18]). Fig. 1 shows a sketch of the time-space diagram of regular service and *A*/*B* skip-stop service in a metro system.

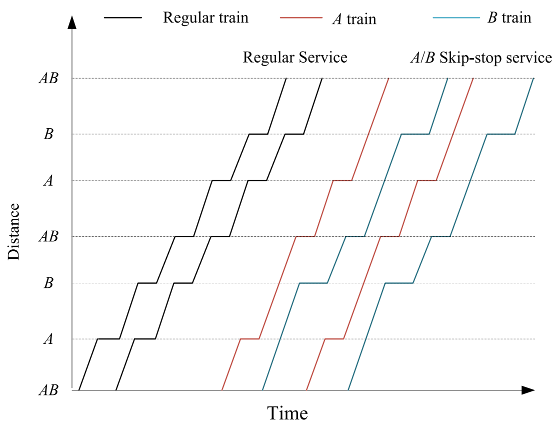

FIGURE 1. Time-space diagrams for regular and *A*/*B* skip-stop service.

However, we must recognize that in the rail system, the travel time between two neigh bor stations and the dwell time at each station is usually a constant value. Quite different with the rail system, the bus system is usually an uncertain system when control methods are absence. An example of such instabilities is the bus bunching induced by the stochastic nature of traffic flows and the imbalance of passenger demand at bus stations. This may cause an increment in the variance of the headways and a consequent worsening of both the magnitude and variability of average waiting times [9]. Besides, Freyss et al. [10] and Lee *et al.* [11] assume that these skip-stop services are symmetric in that they serve the same stations in both directions. Considering the demand imbalance between the two directions, especially in peak period, an asymmetric service for inbound and outbound might benefit passengers and operators more. We want to know, to what extent, this method will improve the efficiency and reliability of the bus systems, how to obtain the optimal distribution of *A*, *B*, *AB* stations and how the service affects the passengers as well as bus system. This paper is devoted to answer these questions.

In daily travel, each passenger appreciates a rapid and reliable trip. Therefore, we attempt to seek for an optimal *A*/*B* skip-stop operation to minimize the average travel time (waiting time and in-vehicle time) of all passengers that arrive at the bus stations during the interested interval. Indeed, each bus stopping scheme is determined by the type of each station, which can be reflected by a set of binary variables. Especially, genetic algorithm is suitable for solving the 0-1 problem. Thus, a genetic algorithm incorporating simulation approach is used to solve the *A*/*B* skip-stop optimization problem in this work.

With regard to the simulation model, we would like to mention that in the existing bus operation simulation model, e.g., Jiang et al. [19], Luo et al. [20], Liu et al. [4] and Chen et al. [5], the O-D (Origin-Destination) properties of the individual passenger are not considered. They simply assume all waiting passengers are qualified to board the dwelling buses and in vehicle passengers alight with given probability at each stopped station. This is obviously not reasonable in real-world bus route with skip-stop operation. Besides, for a traveler whose origin and/or destination are skipped, the transfer time should be accurately recorded in our model. Based on the above insights, we build a much more realistic bus route model, by considering the origin and the destination of each passenger. The input of the individual O-D can be obtained by reading the bus smart card data in a real line.

It is worth noting that the optimal stopping strategies solved in this work are at the planning level, which are pre-planned before the bus is dispatched based on the demand behavior, travel times and stop separation et al. In other words, the skip-stopping pattern is optimal for the interested period and fixed scenario only. With regards to dealing with some undesired behavior in the transport system, such as some stops being out of order or rapid increase of demand, real-time control strategies are necessary.

The remaining parts of the paper are organized as follows. In Sect. 2, we introduce the *A*/*B* skip-stop configuration to the bus system, as well as the main assumptions and notations. Sect. 3 presents a thoroughly model for simulating both the bus operations and the passenger activities. In Sect.4, a genetic algorithm is employed to discover the best distribution of *A*, *B* and *AB* stations with the minimizing average passenger travel time. Sect.5 presents a case study of BRT Line 1 in Beijing, China. Finally, conclusions and future works are given in Sect. 6.

II. A/B SKIP-STOP CONFIGURATION

A. NOTATIONS

The system underlying our model is a two-way bus corridor with island-type platform stations. There are N_s stations in each direction, indicated by $i = 1, 2, \ldots, N_s$, see Fig. 2. Let l denote the bus direction: $l = 1$ refers to direction 1 where buses move from station 1 to N_s; $l = 2$ refers to the opposite direction. We denote the departure frequency in direction l

TABLE 1. List of notation.

State variables:	
$y_{x,i}^{l}$	A binary variable. If x bus skips station i in direction l, $y_{x,i}^{l}=0$; otherwise $y_{x,i}^{l}=1$.
Indices and parameters:	
l	Index of bus direction, $l\in\{1,2\}$
m	Index of bus
n	Index of passenger
i	Index of bus station
x	Index of bus type, $x\in\{A,B\}$
t	Index of time
o_n, d_n	Origin station, destination station of passenger n respectively
k_n	Transfer station of passenger n (if necessary)
N_s	Number of bus stations
f_l	Bus departure frequency in direction l
d_i^l	Distance between station i and its downstream station in direction l
v	Average speed of buses moving between two stations
C	Bus capacity
κ	Time needed to open and close doors
δ	Time loss due to deceleration and acceleration when a bus pulls into and pulls out of a station
a, b	Average alighting, boarding time of one passenger, respectively
Auxiliary variables regarding the evolution of the system:	
e_m^l	Nearest downstream station of bus m in direction l. If bus m is at station i, $e_m^l=\begin{cases} i+1, & l=1\\ i-1, & l=2\end{cases}$
$A_{m,i}^l$, $B_{m,i}^l$	Number of passengers alighting from, boarding bus m in direction l at station i respectively
$\tau_{m,i}^l$	The maximum value between boarding time and alighting time of bus m in direction l at station i
$TA_{m,i}^l$, $TD_{m,i}^l$	Arrival, departure time of bus m in direction l at station i respectively
$T_m^l(t)$	The estimated travel time needed for bus m to reach station e_m^l in direction l at time t
$W_{x,i}^l(t)$	Total number of passengers waiting for x bus in direction l at station i at time t
$\psi_{m,i}^l(t)$	Total number of passengers on bus m in direction l going to station i at time t
$N_p(t)$	Total number of waiting passengers, in vehicle passengers and those passengers having finished trips at time t
$t_a(n)$, $t_d(n)$	Time of passenger n arriving at origin station, leaving the destination station, respectively

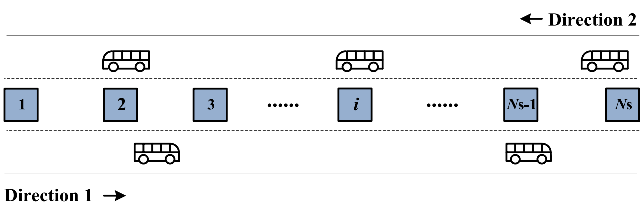

FIGURE 2. Schematic illustration of a two-way bus corridor with island-type platform stations.

as f_l buses per hour, which is assumed to be a constant value in the concerned time interval. The notations are summarized in Table 1.

B. A/B SKIP-STOP SERVICE

1) BUS OPERATION PRINCIPLES

As mentioned before, in the A/B skip-stop service, there are three types of stations (A, B, and AB), and two types of buses (A and B). A (or B) buses only stop at the A (or B) stations and AB stations.

In the A/B skip-stop service, station i should be served by at least one type of bus, i.e.,

$$y_{A,i}^{l}+y_{B,i}^{l}\geq 1,\quad l=1,2;\ i=1,2,\ldots,N_{\mathrm{s}}. \tag{1}$$

In our model, we assume that the original (the first station of a route) and the terminal (the last station of a route) stations should not be skipped, i.e.,

$$y_{x,1}^{l}=y_{x,N_s}^{l}=1,\quad l=1,2;\ x\in\{A,B\}. \tag{2}$$

Moreover, bus overtaking is not allowed. For safety reason, a threshold time headway H_0 should not be violated, i.e.,

$$TA_{m,i}^{l}-TD_{m-1,i}^{l}\geq H_0,\quad l=1,2;\ m=2,3,\ldots,f_l;\quad i=1,2,\ldots,\ldots N_s. \tag{3}$$

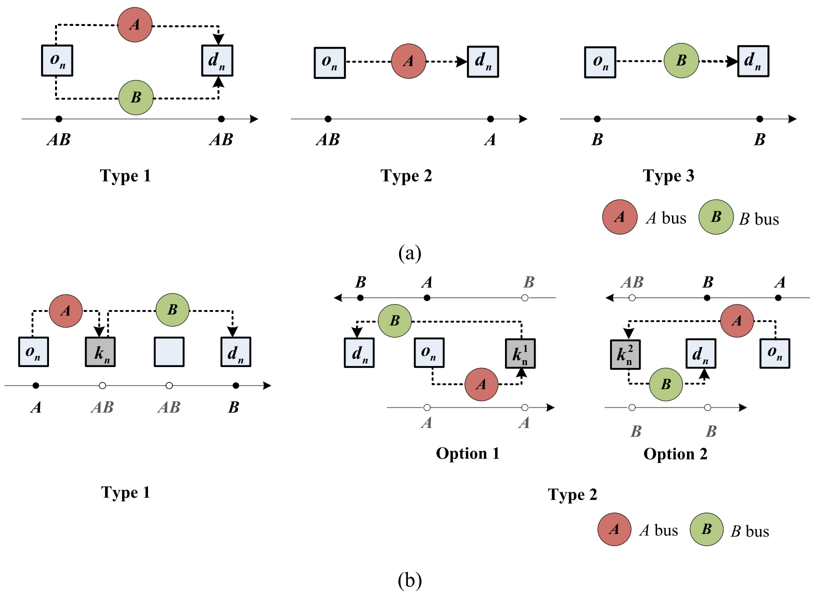

FIGURE 3. **Typical examples of (a) direct trips and (b) trips that need a transfer in an *A*/*B* skip-stop service.**

2) PASSENGER TRIP TYPES

For a regular service, a passenger gets on a coming bus at his/her origin station and alights at his/her destination station. However, in the *A*/*B* skip-stop service, while some passengers can go directly from origin to destination, other passengers need to transfer.

Fig. 3(a) shows three typical examples of direct trips.

Type 1: From an *AB* station to an *AB* station. The passengers can take either *A* or *B* buses to finish their trips.

Type 2: From an *AB* (or *A*) station to an *A* station or vice versa. The passengers must take *A* buses only.

Type 3: From an *AB* (or *B*) station to a *B* station or vice versa. The passengers must take *B* buses only.

Fig.3(b) shows two typical examples of trips that need a transfer, in which passenger n goes from *A* station to *B* station or vice versa.

Type 1: There exist one or more *AB* stations between origin o_n and destination d_n. In our model, it is assumed that the passenger selects the nearest *AB* station from origin o_n as transfer station.

Type 2: There is no *AB* station located between o_n and d_n. In this case, the passenger needs to find a transfer station and there are two options: One is to choose the transfer station k_n^1 beyond o_n, the other is to choose k_n^2 beyond d_n. We assume that the passenger selects the one with a smaller number of passing stations. As shown in Fig.3(b), the number of passing stations for option 1 and option 2 are $2k_n^1 - (o_n + d_n)$ and $(o_n + d_n) - 2k_n^2$, respectively. If the numbers are equal, the two options will be selected with equal probability.

III. SIMULATION MODEL

In this section, we present a realistic simulation model of the bus route system considering the origin and destination of each passenger. Moreover, the detailed processes of passengers' boarding/alighting and buses' moving/stopping have been depicted. We denote t, t_0 and t_f as the current time, start time and end time of the interested interval, respectively.

A. ASSUMPTION

For simplicity, the following assumptions are made:

- All the buses are homogenous, they have identical capacity and average operating speeds.
- Passengers' arrival rates at each station do not change over time in the interval of interest.
- Passengers will board the first available bus unless the vehicle capacity is reached. They obey the principle of first arrive first board.
- The boarding/alighting time for each individual is homogeneous, which is consistent with other researches, e.g., [3]–[6], [14], [19], [20].
- Boarding and alighting take place at the front and rear doors, respectively. Thus, the passenger service time of a bus at a station is a maximum between boarding time and alighting time.

B. PASSENGER ACTIVITIES

The simulation keeps track of individuals at the stations and in the buses, for example, each passenger's arrival time at origin station $t_a(n)$ and departing time at destination station $t_d(n)$, the number of waiting passengers at each station for each time step. When a new passenger n arrives at station o_n, his/her arrival time at origin station is $t_a(n) = t$, and the total number of passengers increases by one: $N_p(t) = N_p(t-1) + 1$.

1) NON-TRANSFERRING PASSENGER

The non-transfer passenger can take one bus from his/her origin station to destination station directly. For passenger n, we assume the direction from o_n to d_n is l.

a: PASSENGERS' ARRIVAL

When a new passenger n arrives at origin station, (a) if his/her destination allows him/her to take either A or B bus to reach d_n, then the total numbers of passengers waiting for A and B bus both increase by one: $W^l_{A,o_n}(t) = W^l_{A,o_n}(t-1) + 1$ and $W^l_{B,o_n}(t) = W^l_{B,o_n}(t-1)+1$; (b) if he/she can only board x bus, then the number of passengers waiting for x bus increases by one: $W^l_{x,o_n}(t) = W^l_{x,o_n}(t-1) + 1, x \in \{A, B\}$.

b: PASSENGERS' BOARDING

If passenger n has boarded bus m, the number of passengers on bus m that destine for station d_n increases by one: $\psi^l_{m,d_n}(t) = \psi^l_{m,d_n}(t-1)+1$. Moreover, (a) if his/her destination allows him/her to take either A or B bus, then $W^l_{A,o_n}(t) = W^l_{A,o_n}(t-1) - 1$ and $W^l_{B,o_n}(t) = W^l_{B,o_n}(t-1) - 1$; (b) if he/she can only board x bus, then $W^l_{x,o_n}(t) = W^l_{x,o_n}(t-1)-1$, $x \in \{A, B\}$.

c: PASSENGERS' ALIGHTING

Once passenger n arrives at d_n, he/she will alight the bus and leave. We assume that those passengers on one bus destining for the common station alight simultaneously, namely: $t_d(n) = TA^l_{m,d_n} + \kappa/2 + (a \cdot A^l_{m,d_n})/2$, where TA^l_{m,d_n}, $\kappa/2$ and $a \cdot A^l_{m,d_n}$ indicate the arrival time, time for opening doors and alighting time of bus m in direction l at station d_n, respectively.

2) TRANSFERRING PASSENGER

The trip of a transferring passenger n consists of two non-transferring trips: ① from o_n to k_n; ② from k_n to d_n. Due to the island-type platform facility, transferring passengers wait at station k_n for the second bus immediately after alighting from the first bus with no need to walk to other platforms. Hence, the total waiting time (or in-vehicle time) for transferring passenger n equals to the sum of the waiting time at site o_n (or in-vehicle time from site o_n to site k_n) and that at site k_n (or that from site k_n to site d_n) .

Here, we remark on the calculation of the transfer time in a more common bus line where not all stops are island-type stations. In such a case, a transferring passenger experience an additional walking time when he/she has to go to the oppsite direction to take the second bus and his/her transferring station is not island-based. The additional walking time for the indivual can be calculated by the distance between the two stops being divided by the average passenger walking speed.

C. BUS OPERATIONS

For direction 1 (or 2), the first bus departs at time t_0 and is set as an A bus. When a new bus m of type x starts its operation from original station at time t, it will dwell at the station for passenger boarding immediately, and the arrival time will be: $TA^1_{m,1} = t$ (or $TA^2_{m,N_s} = t$).

1) BUS MOVING

When bus m is moving between two neighboring stations, the remaining travel time to reach next station i decreases with time: $T^l_m(t) = \max\ (T^l_m(t-1) - 1, 0)$. When $T^l_m(t) = 0$, (a) if $m = 1$, since there is no bus in front, bus m moves forward immediately; (b) if $m > 1$, one needs to check whether constraint (3) is satisfied: bus m cannot move forward unless bus $m-1$ has left station i for a certain time H_0.

Now we need to check whether bus m skips the station or not.

① If $y^l_{x,i} = 0$, the bus skips station i, then $TA^l_{m,i} = TD^l_{m,i} = t$. The estimated travel time $T^l_m(t)$ to reach its next station is set as follows: If $y^l_{x,e^l_m} = 0$ (i.e., the bus also skips next station e^l_m), then $T^l_m(t) = \frac{d^l_i}{v}$. Otherwise, $T^l_m(t) = \frac{d^l_i}{v} + \frac{\delta}{2}$. Here $\frac{\delta}{2}$ denotes additional delay due to deceleration at next station.

② If $y^l_{x,i} = 1$, bus m will dwell at station i, then $TD^l_{m,i} = t$.

2) BUS DWELLING

The dwelling process of bus m at station i is classified into four steps as follows:

① If $t \le TA^l_{m,i} + \kappa/2$, the bus is opening the doors. The number of alighting and boarding passengers are

$$A^l_{m,i} = \psi^l_{m,i}(t)$$

and

$$B^l_{m,i} = \begin{cases} \min(C - \sum_{j=e^l_m}^{N_s} \psi^l_{m,j}(t), W^l_{x,i}(t)), & l = 1 \\ \min(C - \sum_{j=e^l_m}^{1} \psi^l_{m,j}(t), W^l_{x,i}(t)), & l = 2, \end{cases},$$

respectively.

We denote flag $= 1$ if $B^l_{m,i} = W^l_{x,i}(t)$, which means that all waiting passengers can board the bus. Otherwise, flag $= 0$, which means that the bus cannot accommodate so many waiting passengers. Thus, some passengers need to wait for the subsequent bus.

② Passenger's alighting and boarding activities take place.

If flag $= 0$, then the alighting and boarding time is $\tau^l_{m,i} = \max(b \cdot B^l_{m,i}, a \cdot A^l_{m,i})$.

If flag $= 1$, when all waiting passengers have boarded or all alighting passengers have alighted, we need to check whether there are new passengers arriving or not. If yes, we need to judge whether all the newcomers can board. Then we need to calculate the additional boarding time of new passengers. This similar process repeats until the bus is full or no new passenger arrives. We denote the number of additional passengers getting on bus as B_{add}. Thus, the alighting and boarding time is $\tau^l_{m,i} = \max(b \cdot (B^l_{m,i} + B_{add}), a \cdot A^l_{m,i})$

③ If $TA^l_{m,i} + \kappa/2 + \tau^l_{m,i} < t \leq TA^l_{m,i} + \kappa + \tau^l_{m,i}$, the bus is closing the doors.

④ If $t > TA^l_{m,i} + \tau^l_{m,i} + \kappa$, the bus is ready for pulling out of the station i, thus $TD^l_{m,i} = t$.

If station i is the terminal station, bus m will leave the route. Otherwise, the bus will leave for its next station e^l_m, (a) if $y^l_{x,e^l_m} = 0$ (i.e., the bus skips station e^l_m), then $T^l_m(t) = \frac{d^l_i}{v} + \frac{\delta}{2}$. Here $\frac{\delta}{2}$ denotes additional delay due to acceleration from station i; (b) otherwise $T^l_m(t) = \frac{d^l_i}{v} + \delta$. Here δ denotes additional delay due to acceleration from station i and deceleration at next station.

IV. OPTIMIZATION METHOD

A. OBJECTIVE FUNCTION

The optimization problem is to minimize the average travel time of all passengers that arrive at the bus station during the interested interval. The objective function is defined as

$$\min Z = \frac{\sum_{n=1}^{N_p(t_f)} (t_d(n) - t_a(n))}{N_p(t_f)}, \tag{4}$$

where, $N_p(t_f)$ is the total number of passengers arriving at all the bus stations from time t_0 to t_f, $t_a(n)$ and $t_d(n)$ are arrival time and departing time of passenger n, respectively. In our work, the A/B skip-stop optimization problem is to determine the type of each station.

B. SOLUTION METHOD

For a bidirectional bus route with N_s stations, excluding the original and the terminal stations, the number of possible configurations of stations is $3^{2(N_s-2)}$, which is beyond enumeration when N_s is not very small. For example, when $N_s = 17$ as in the Case study, the number equals to 2.0589×10^{14}. Thus, we use a heuristic Genetic Algorithm (GA) to solve the problem. To design a GA solving the A/B skip-stop optimization problem, some details are described below.

1) CHROMOSOME STRUCTURE

In the A/B skip-stop problem, we define $\begin{bmatrix} y^l_{A,i} \\ y^l_{B,i} \end{bmatrix}$ as a gene to indicate the type of station i in direction l, and $2N_s$ genes constitute a chromosome. Note that a gene must satisfy the constraint (1) and (2). Therefore, the genes for original and terminal stations are:

$$\begin{bmatrix} y^1_{A,1} \\ y^1_{B,1} \end{bmatrix} = \begin{bmatrix} y^1_{A,N_s} \\ y^1_{B,N_s} \end{bmatrix} = \begin{bmatrix} y^2_{A,1} \\ y^2_{B,1} \end{bmatrix} = \begin{bmatrix} y^2_{A,N_s} \\ y^2_{B,N_s} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix},$$

and the genes for other stations can be $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ (AB station) or $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ (A station) or $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ (B station).

The second step in the genetic algorithm is to initialize the population of chromosomes. In this model, the chromosome is generated randomly.

2) EVALUATION

To evaluate a chromosome, we run the simulation model described in section III over the period of interest, and calculate each passengers' travel time. To reduce the stochastic fluctuations, we obtain the mean value by averaging over 100 initial configurations in simulations.

3) CROSSOVER AND MUTATION OPERATIONS

The crossover operator exchanges information between chromosomes. For each two chosen chromosomes, sample an integer number between 1 and $2N_s$, denoted by $\overline{j_1}$ and $\overline{j_2}$ respectively. Then exchange these genes from $\overline{j_1}$ to $\overline{j_2}$ in the two chromosomes with crossover probability π.

To carry out the mutation operation, we randomly choose a gene representing an intermediate station, and then replace it by a new one with mutation probability w. If station i in direction l is an A station, it can mutate into a B station or AB station randomly.

4) SELECTION

A deterministic selection strategy is adopted. We sort parents and offspring in ascending order and select q chromosomes as a new population, where q is the population size. We execute $g_{\max}$ iterations, and retain the chromosome with minimum objective value.

V. CASE STUDY, RESULTS, AND ANALYSIS

A. BRT LINE 1 IN BEIJING

The proposed method is now applied to optimize a real-world bus corridor of the BRT Line 1 in Beijing, China. The 15.6 km long line serves 17 island type stations in each direction, where Demaozhuang Station and Qianmen Station are denoted by Station 1 and Station 17, respectively. In this case, the northbound corridor and the southbound corridor is set as direction 1 (D1), and direction 2 (D2), respectively. All stations of BRT Line 1 and the distance d^l_i between two consecutive stations are shown in Fig. 4.

We focused on studying the morning peak from 7 a.m. to 9 a.m. on the weekdays and collected the BRT smart card data during the two hours period. In these data, each station is numbered by an integer representing its distance (kilometers) to the original station, and each passenger's origin station number and destination station number are recorded. Since stations locate uneven in the bus line, two neighboring sites may share a common number. OD demands between two stations that have unique station number can thus be obtained. However, if origin and/or destination site share a station number with others, we carried out an assisted field survey to estimate the OD demands.

Fig. 5 shows the passenger demand (boarding and alighting numbers) and load profile[1] at each station. One can see that

[1] Load profile indicates the total number of passengers on board of vehicles operating during period of interest when they leave a specific bus station.

TABLE 2. Performance of the optimal *A/B* skip-stop service under different scenarios.

Scenario	Direction 1 (min)			Direction 2(min)			Objective(min)
	Waiting Time	In-vehicle Time	Travel Time	Waiting Time	In-vehicle Time	Travel Time	
Regular service	2.67	24.84	27.51	1.88	15.89	17.77	24.86
USS1	2.17 (-18.73%)	21.95 (-11.63%)	24.12 (-12.32%)	1.91 (1.60%)	16.06 (1.07%)	17.97 (1.13%)	22.45 (-9.69%)
USS2	2.68 (0.37%)	24.86 (0.08%)	27.54 (0.11%)	2.02 (7.45%)	15.05 (-5.29%)	17.07 (-3.94%)	24.69 (-0.68%)
BSS	2.19 (-17.98%)	21.99 (-11.47%)	24.18 (-12.10%)	2.12 (12.77%)	14.37 (-9.57%)	16.49 (-7.20%)	22.08 (-11.18%)

Note: the number in brackets represents the percentage increase/ decrease compared with regular service.

FIGURE 4. BRT line 1 in Beijing, China.

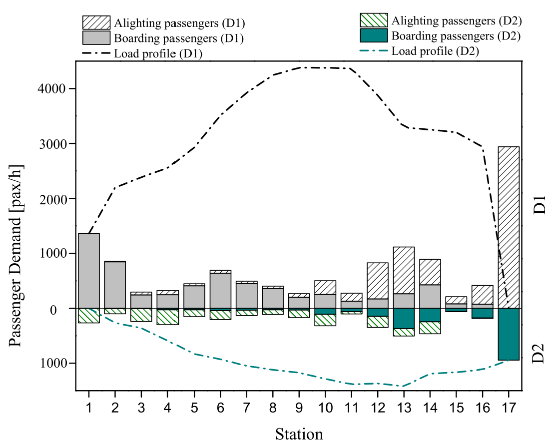

FIGURE 5. Passenger demand and load profile at each station during 7:00-9:00 a.m.

there is a large imbalance in the passenger demands between the two directions of BRT Line 1. This is because the majority of passengers commute from residential areas to their work-places and schools.

B. PARAMETER SETTINGS

In the simulation, the initial and final time t_0, t_f correspond to 7:00 a.m. and 9:00 a.m. respectively. The arrival rates of passengers are set to be proportional to the OD demands.

Other parameters surveyed from the real bus line are set as follows: bus capacity $C = 180$, average bus operation speed $v = 10\ m/s$, additional dwell time $\kappa = 10\ s$, deceleration and acceleration time $\delta = 20\ s$, average boarding and alighting time are $b = 2.0s$ and $a = 1.5\ s$ respectively, the threshold time headway H_0 in Eq.(3) is set as 6 s [5]. The four parameters in genetic algorithms: $q = 60$, $g_{\max} = 1000$, $\pi = 0.2$ and $w = 0.01$.

In order to simplify the analysis, we set the same bus frequency f for the two directions, that is $f_1 = f_2 = f = 20$buses/h. Particularity, the bus frequency does not change before and after implementing A/B skip-stop service in this work.

C. NUMERICAL RESULTS AND DISCUSSION

In the next subsections, we discuss three different A/B skip-stop scenarios:

- Skip-stop service in D1 and regular service in D2 (USS1).
- Skip-stop service in D2 and regular service in D1 (USS2).
- Bidirectional A/B skip-stop service (BSS).

The former two scenarios constitute unidirectional A/B skip-stop service (USS).

1) OPTIMAL CONFIGURATION OF THE STATIONS

Fig. 6 depicts the optimal configuration of the stations under the three skip-stop scenarios. The number of A and B stations for USS1, USS2 and BSS are 12, 6 and 20 (12 for D1 and 8 for D2) respectively. Moreover, in each case, the numbers of A stations and B stations are close, and these two types of stations usually alternate with each other. As a result, buses are properly coordinated to keep safe separation and bus bunching is significantly reduced.

As illustrated in Table 2, A/B skip-stop service in the BRT Line 1 corridor is effective to reduce the average travel

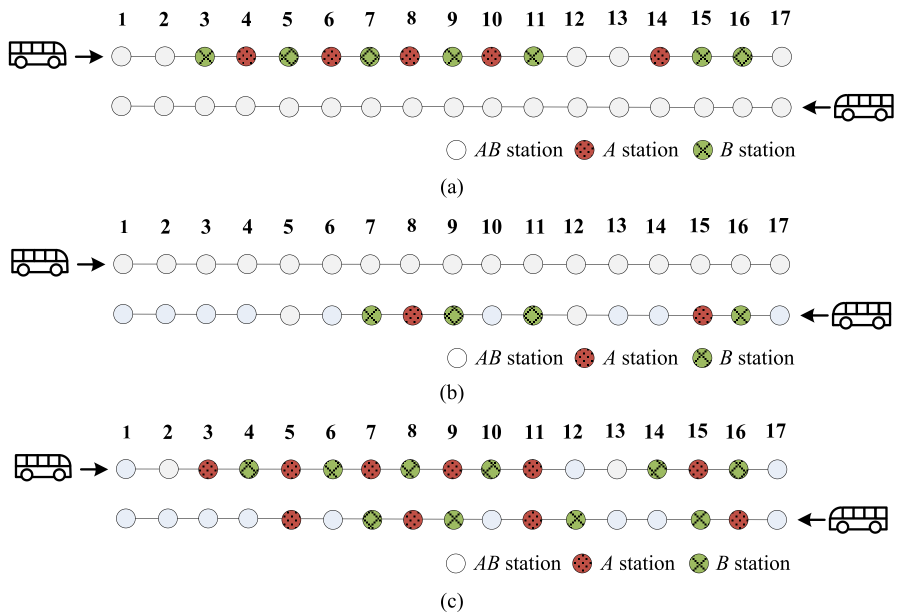

FIGURE 6. Optimal configuration of stations. (a) USS1. (b) USS2. (c) BSS.

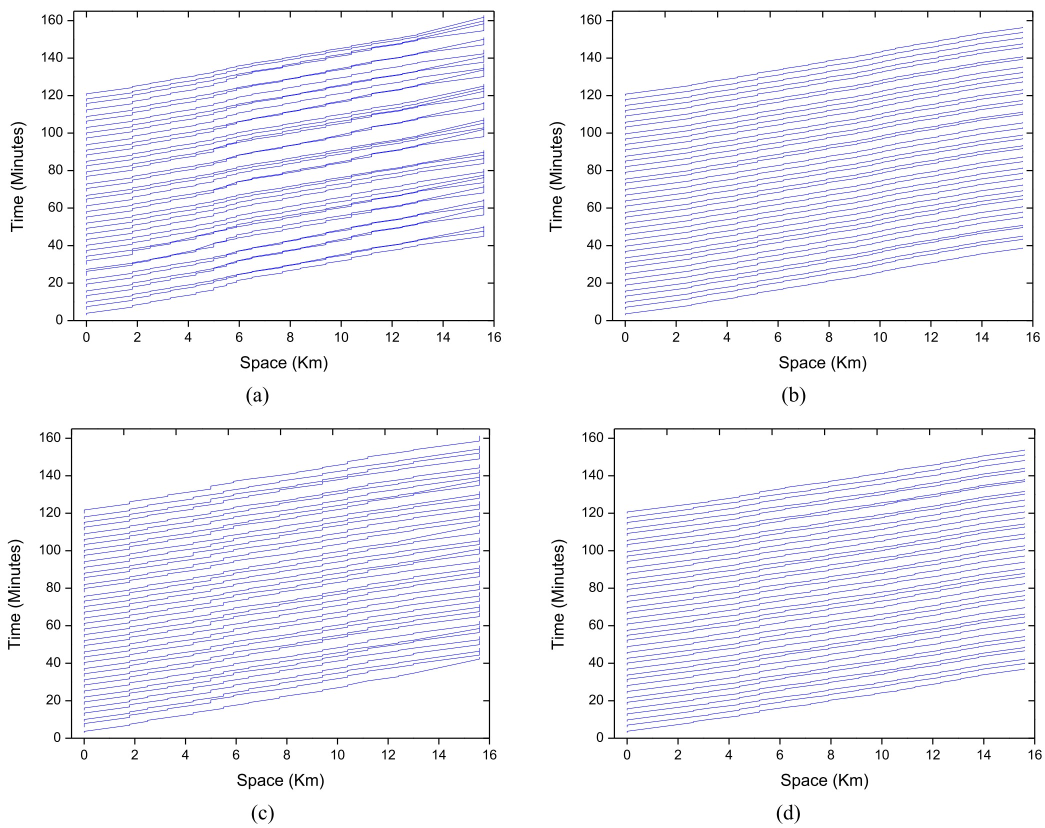

FIGURE 7. Trajectories of buses under different service: (a) regular service for D1; (b) regular service for D2; (c) BSS for D1; and (d) BSS for D2.

time under either unidirectional or bidirectional skip-stop scenarios. For the unidirectional cases, USS1 outperforms the regular service by 9.69% while USS2 only 0.68%. However, as a cost, the average travel time of the other direction increases by 1.13% (or 0.11%) in the case of USS1 (or USS2). This is because, as mentioned before, some passengers have

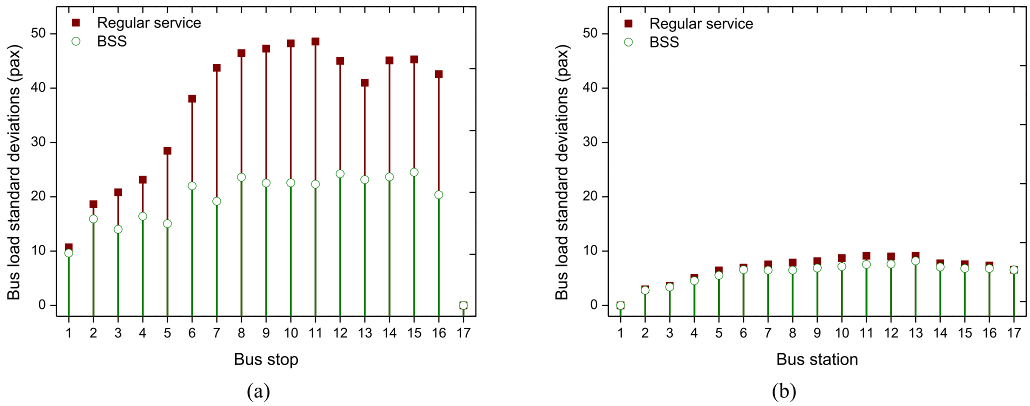

FIGURE 8. Bus load standard deviations under regular service and BSS. (a) D1. (b) D2.

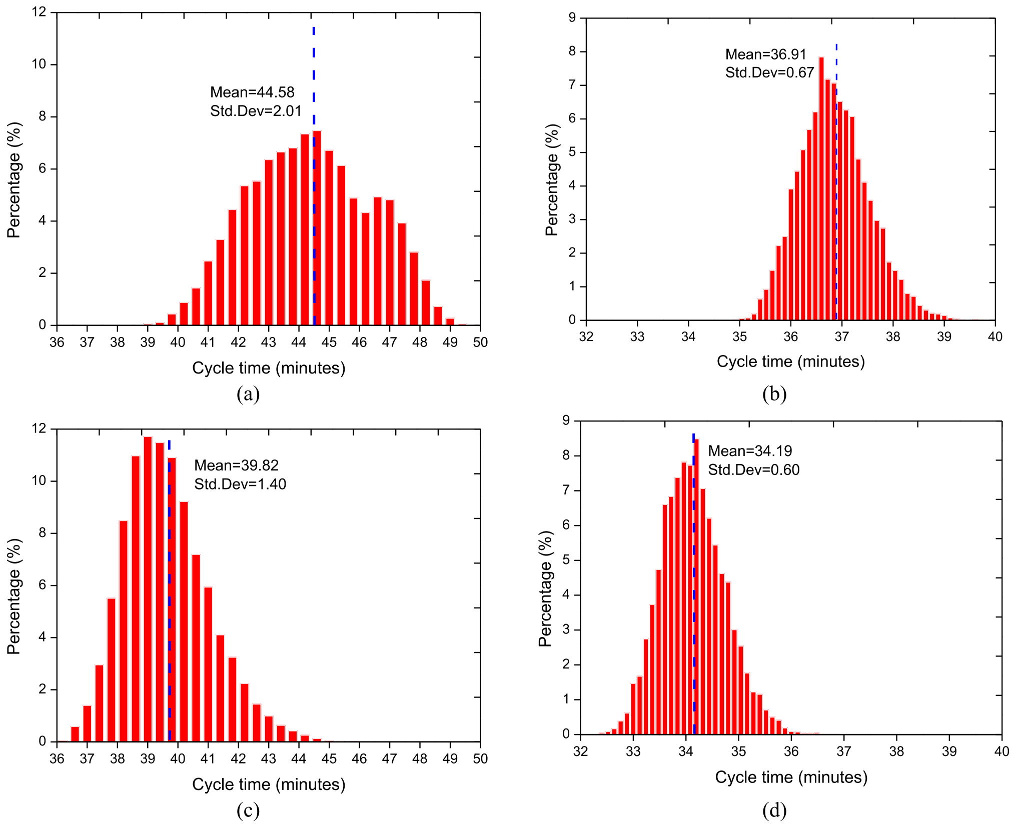

FIGURE 9. Distribution of cycle time for different services in both directions: (a) regular service for D1; (b) regular service for D2; (c) BSS for D1; and (d) BSS for D2.

to transfer by taking the buses in the opposite direction, which increases the queuing passengers and dwell time at stations of D2 (or D1), finally leads to extra waiting time and in-vehicle time, as well as passenger travel time. In contrast, bidirectional skip-stop service can improve the performance of both directions, and achieves a greater improvement with an objective saving of 11.18%, where D1 and D2 benefit savings of 12.10% and 7.20% respectively.

Fig. 7 shows typical trajectories of buses under different service scenarios. One can see that serious bus bunching emerges if D1 is served by regular service. In contrast, D2 does not suffer from bus bunching due to its low demand. When BSS service is implemented, the bus bunching in D1 is reduced. As a result, the performance has been significantly improved in D1 than D2. This is consistent with the results shown in Table 2 that D1 achieves greater passenger waiting time saving and in-vehicle time saving from *A*/*B* skip-stop service than D2, e.g., D1 achieves an in-vehicle time saving of 11.63% in the USS1, while D2 gains 5.29% in the USS2; BSS has a reduction of 11.47% for D1 and 9.57% for D2.

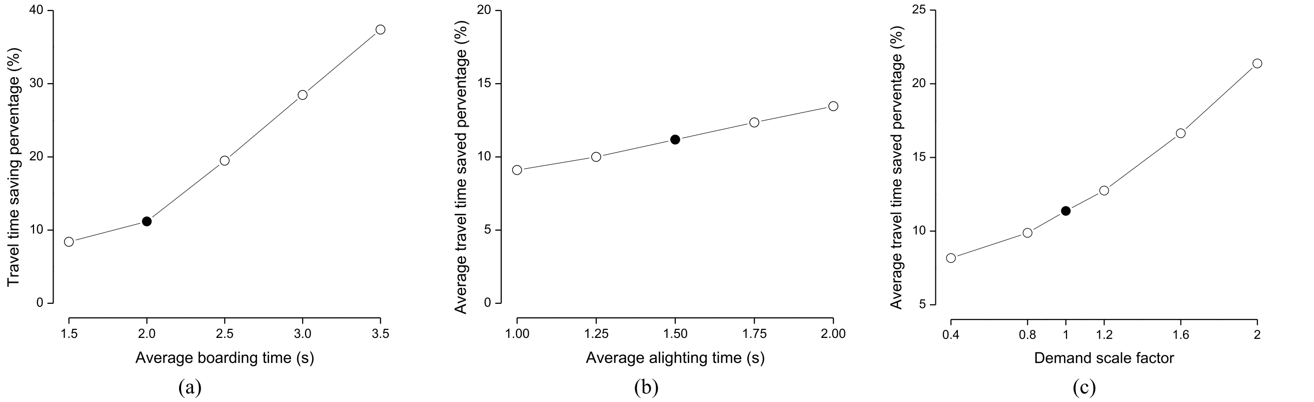

FIGURE 10. Influences of different parameters on the passenger average travel time saved percentages: (a) average boarding time; (b) average alighting time; and (c) Passenger demand. In (c), the demand is the product of demand scale factor and base demand as in Fig.5.

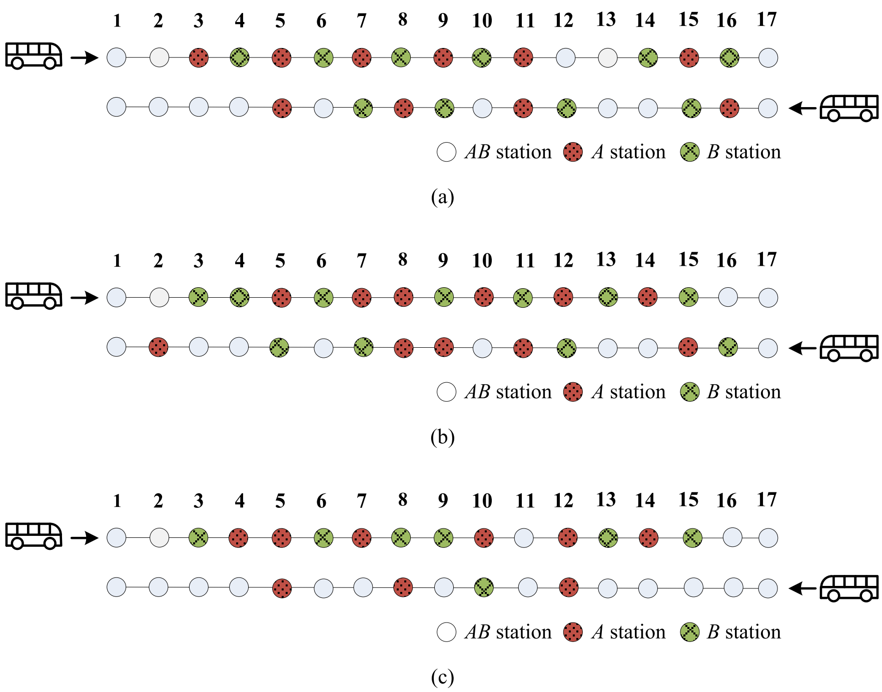

FIGURE 11. Optimal configuration of stations for scenarios with different proportions of transferring passengers changing origins or destinations. (a) $p_{od} = 0$. (b) $p_{od} = 0.3$. (c) $p_{od} = 0.5$.

Since BSS performs better than USS, in the next section, we will further analyze the influences of implementing BSS on the bus system.

2) PERFORMANCE EVALUATION OF BSS

① Bus load standard deviations: Fig.8 shows the load standard deviations of all buses under regular service and BSS. The figure indicates that BSS leads to smaller load variability at stations in both directions. Note as well that variations in D1 are much larger than that in D2 since the bunching is reduced in D1.

② Cycle time distribution: Fig.9 shows the distribution of the cycle times of all buses. The results demonstrate that skip-stop service reduces the average cycle time. Under the regular service, the average cycle time is 44.58 (36.91) min in D1 (D2), which reduces to 39.82 (34.19) min under BSS, with a reduction of 10.68% (7.37%). Moreover, BSS yields a narrower cycle time distribution and a lower standard deviation than the regular service for both directions. These results suggest that A/B skip-stop service also benefits bus companies since the low variability allows a smoother and more robust operation and planning at the terminals. Furthermore, shorter bus cycle time means that demand can be met with fewer vehicles and therefore lower costs.

3) SENSITIVITY ANALYSIS

Now we carry out a sensitivity analysis with respect to average boarding time, average alighting time and passenger demand. As shown in Fig. 10, one can see that the improvement (in terms of percentage of passenger averaged travel time saved) of BSS over regular service increases with the increase of the three parameters. That happens because, with the increase of the three parameters, each bus will dwell longer at each station, especially at some large demand stations, where the bus can be more easily caught up and then bus bunching becomes more serious. This suggests that a more unstable bus system can benefit more from BSS.

4) ELASTIC DEMAND ANALYSIS

In the above discussion, passenger demand at each station is assumed to be fixed over time in the interval of interest. However, in reality, individuals may change their original trips due to some other external factors, e.g., finding a free seat in the upstream station, changing origins or destinations to avoid transferring inconvenience et al. In turn, the variation of passenger demand at each station urges the transit manager to modify the control strategies to minimum its operation objectives.

For example, in the A/B skip-stop operation, we assume the proportion of transferring travelers changing their origins or destinations is a known value, indicted by p_{od}. Moreover, those passengers are assumed to take bicycles (with mean speed of 5 m/s) from their primary origins (or new destinations) to new origins (or primary destinations), and prefer to find a new origin or destination with minimum bicycle traveling time (or distance). Based on these conditions, we could obtain the optimal schemes with different value of p_{od}, seen in Fig.11. Clearly, the results confirm that the proportion of transferring passengers changing trips has an impact on the optimal configuration of stations indeed.

VI. CONCLUSIONS

This paper presented a simulation-based optimization method to design A/B skip-stop service for an island-type bus corridor. In the simulation model, we have considered each passenger's origin and destination, and bus capacity constraint. The model depicts the details of each passenger's boarding/alighting, as well as each bus's moving/stopping. A genetic algorithm was developed to solve the optimization problem to minimize the average passenger travel time. We have compared two different cases: BSS where A/B skip-stop services are applied to both directions, and USS where A/B skip-stop service is implemented in only one direction.

Using real-world data from BRT Line 1 in Beijing, we validated the effectiveness of the optimization method. The numerical example indicated high demand direction benefits more from A/B skip-stop service than the lower demand one. Moreover, it was shown that BSS outperforms USS in terms of average travel time saved for passengers in both directions. Simulation results also suggested that BSS service is more comfortable and reliable than regular service. To passengers, bus loading is more balanced under BSS. To bus company, BSS reduces the average cycle time and its variability. Later, sensitivity analysis shows that the potential benefit of BSS increases if average boarding time, average alighting time or passenger demand increases. Finally, the elastic demand that transferring passengers may change their origins or destinations has been considered, it is seen that the passengers' travel choices impact the optimal stopping schemes.

In the future work, some extensions might be considered. For example, (a) we assume an equal bus frequency for two directions. However, due to the passenger demand imbalance, different bus frequency might be more practical; (b) in real cases, some stops might be off island-type platform stations, thus exploring a hybrid-stop bus system has more practical significances.

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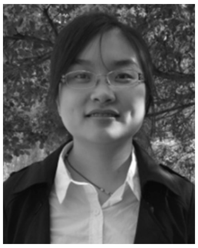

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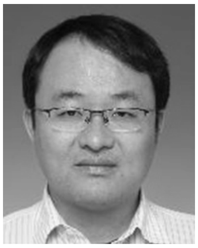

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