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Operational Design for a Real-Time Flexible Transit System Considering Passenger Demand and Willingness to Pay

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ABSTRACT Internet-based transit services have the potential to enable fully connected, safe, reliable, efficient, and flexible service in the public transit system. The flexible transit system (FTS) allows passengers to make individual travel requests and receive customized door-to-door service by specifying their origins and destinations (OD), departure time range, and willingness to pay (WTP). Unlike the uniform and stable WTP in our previous paper , we consider an exponential decay function for the real pickup locations of passengers, and we proposed a joint design of two-level bus stops in temporal and spatial variations of travel demands. To ensure practical applications of this real-time FTS model, we combine the traversing method and the improved tabu search algorithm. A numerical example from Guangzhou is conducted to demonstrate the applicability of the proposed model and its effectiveness in reducing system cost.

INDEX TERMS Public transit, flexible transit system, willingness to pay, real-time response, operational design.

I. INTRODUCTION

Most existing public transit systems (PTSs) face the conflicting objectives of cost-efficient operations and high-quality service [3]. Further, existing transit systems primarily use fixed bus lines and bus stops, which are established according to specific coverage rules that may result in a low economic efficiency for some bus stops.

With the increased availability of mobile Internet and electronic payment, Internet-based flexible transit systems (FTSs) deliver a vision for fully connected, safe, reliable, and efficient service in PTSs [1]. These advantages make it possible for different user groups (e.g., the elderly, disabled, pregnant, and high-income groups) to choose the way that they participate in bus travel. These different user groups have different levels of willingness to pay (WTP) in the transit system [2], which are closely related to the service they get compared to their demand requests. However, it is difficult for the existing PTSs to meet these individual demands. Since FTSs do not have fixed routes or schedules, they can be customized and dispatched based on transport requests.

To increase income, a growing number of bus companies are considering operation strategies. One is transforming the existing PTS (FIGURE 1.a) into an FTS (FIGURE 1.b/c). In an FTS, we can reduce the number of high-level fixed stops (i.e., A-level bus stops that have guaranteed visits) and set more flexible bus stops (i.e., B-level bus stops that have selected visits). The other is setting a more flexible ticket fare structure, which considers a maximum fare that is more close to the passenger WTP (i.e., FIGURE 1.c).

The alternate application of a PTS policy and an FTS policy [4] can lead to a win-win situation for both passengers and bus companies, especially in areas that lack para-transit systems or in off-peak hours. FTS are a new product for both passengers and bus companies. Therefore, the leaders of bus companies hope to learn how to combine existing buses with Internet buses to satisfy the fluctuant passenger flow in

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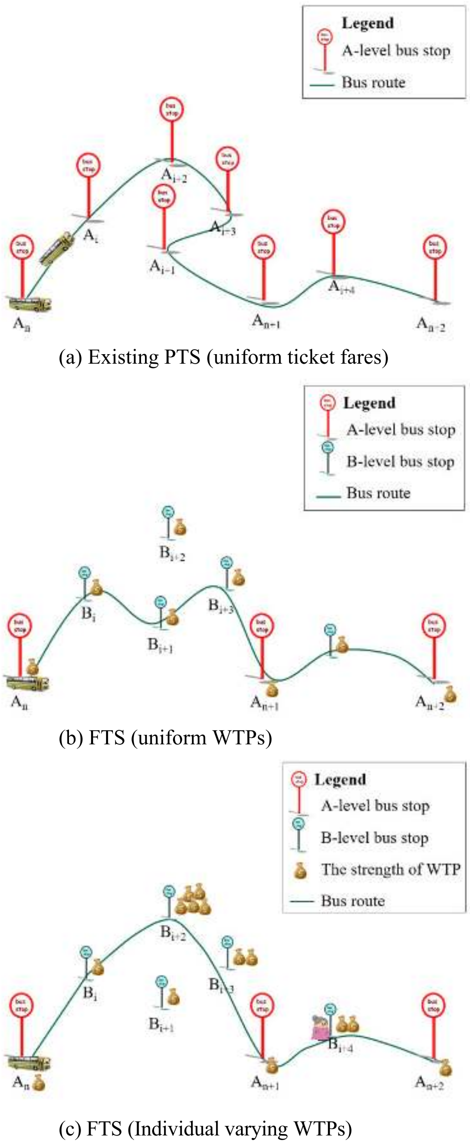

FIGURE 1. **Comparison of the existing PTS and FTS.**

various service cycles and determine when is the appropriate time point to transform transit bus lines into flexible bus lines. In Section 4 we provide ideas for calculating the return on investment under the operation system and model proposed in this paper.

A. LITERATURE REVIEW

Early solutions in these fields date to 40 years ago and have developed steadily [5]–[12]. These solutions include dial-a-ride (DAR) [3], [13]–[17], demand response transit systems (DRTSs) [9], [18], [19], and FTSs [20]–[23]. Motivated by concerns for the environment and new developments in technology, there has been a resurgence of interest in FTSs [3]. TABLE 1 summarizes the previous studies on FTSs and their route deviations in recent years. The findings can be briefly summarized as follows:

1. The operational system can be roughly classified into four categories—static-deterministic, static-stochastic, dynamic-deterministic, and dynamic-stochastic—according to the excellent review paper by Ho et al. [3]. In the present paper, the problem is a dynamic-deterministic problem: first, the decision-maker is allowed to respond to this new information; second, the decision-maker knows the set of all potential demands as well as whether or not each potential passenger will show up and the exact duration of every operation.
2. Several papers optimize only a single objective [13], [15], [24]–[28], while other studies have incorporated multiple objectives in which the decision-maker must determine an optimal solution among different goals [4], [12], [17], [29]–[33]. The most popular objectives are to minimize the service provider's operating costs and/or users' inconvenience metrics, and only a small number of studies consider vehicle emissions as well. Moreover, we considered both the system costs as well as the passengers' time costs.
3. However, it is unfortunate that these systems did not include fully flexible passengers' WTPs and real-time two-way communication. We can perform more in-depth studies on flexible systems in a world with widespread mobile phones and Internet services. This paper introduces passengers with various demands [1] as well as digressive WTPs [34] into the flexible system.

The solutions to this type of problem fall into three categories, exact algorithms, heuristic algorithms, and simulation techniques, as stated in TABLE 2. The enumeration method [38], which is a precise algorithm, fails when the situation of the corresponding case is too large. Most of the exact methods for the DARP are based on a B&B framework [3]. The computational time of a B&B procedure can be exponential in the worst case. Additionally, the computational effort of the algorithm should be minimal to be able to produce optimal solutions in a short time, even though the number of customers is large [30]. The heuristic algorithm generates an initial solution according to the given constraint condition first and then improves the performance of the initial solution based on an algorithm to obtain a satisfactory solution. The algorithms that optimize the initial solution are mostly intelligent algorithms, such as tabu search, ant colony, simulated annealing, and genetic algorithms. The tabu search algorithm has a strong ability to search for this model. Here, we utilize a combination of the traversal method as well as a tabu search algorithm to reach a balance of solving speedily and precisely.

B. CONTRIBUTIONS

To realize the vision of FTSs, we propose a joint design of two-level bus stops in low traffic volume times or areas to achieve the optimal tradeoff between general bus fare income

TABLE 1. Summary of the previous studies on FTS (route deviation).

Year	Reference	Problem category*	Selective visits	Single (S)/Multi (M) bus fares	Varied WTPs	Single (S)/Multi (M) vehicles	Single (S)/Multi (M) objectives	Time windows
2007	Jorgensen et al. [12]	SD	-	S	-	M	M	√
2008	Xiang et al. [15]	DS	√	S	-	M	S	√
2010	Beaudry et al. [29]	DD	-	S	-	M	M	√
2011	Häme [30]	SD	-	S	-	S	M	√
2011	Heilporn et al. [24]	SS	-	S	-	S	S	√
2012	Berbeglia et al. [25]	DD	√	S	-	M	S	√
2012	Parragh et al. [36]	SD	-	S	-	S	M	√
2013	Kirchler and Wolfler Calvo [32]	SD	√	S	-	M	M	√
2013	Reinhardt et al. [37]	SD	√	S	-	M	M	√
2014	Feng et al. [26]	SD	-	S	-	M	S	√
2014	Schilde et al. [33]	DS	-	S	-	M	M	√
2015	Liu et al. [13]	SD	-	S	-	M	S	√
2015	Santos and Xavier [17]	DD	√	S	-	M	M	√
2017	Lim et al. [38]	SD	-	S	-	M	S	√
2017	Molenbruch et al. [28]	SD	-	S	-	M	S	√
2019	Shen et al. [4]	SD	√	M	-	S	M	√
2019	Pei et al. [39]	DS	-	M	-	M	S	√
2019	Pei et al. [1]	SD	√	M	-	S	M	√
-	This paper	DD	√	M	√	S	M	√

*Note: SD = static-deterministic; DS = dynamic- stochastic; DD = dynamic-deterministic; SD = static-stochastic.

TABLE 2. Summary of the previous studies on FTSs (solution method).

Solution method	Classification	Reference
Exact algorithms	Enumeration method	Wu et al. 2016[41]; Pei et al. 2019 [1]
	Branch-and-bound	Cordeau 2006[42]; Ropke et al., 2007[43]; Parragh 2011[36]; Braekers et al., 2014[44]; Braekers and Kovacs, 2016[45]; Liu et al., 2015[13]; Hu and Chang 2015[46]; Qu and Bard 2015[47]; Gschwind and Irnich 2015[48]
Heuristic algorithms	Tabu search	Beaudry et al., 2010[29]; Ho and Haugland, 2011[49]; Guerriero et al., 2013[50]; Paquette et al., 2013[51]; Kirchler and Wolfler Calvo, 2013[32]; Detti et al., 2017[52]
	Simulated annealing	Mauri et al., 2009[53]; Zidi et al., 2012[54]; Reinhardt et al., 2013[37]; Braekers et al. 2014[44]
	Neighborhood search	Parragh, 2011[36]; Muelas et al., 2013[55]; Lehuédé et al., 2014[56]; Masson et al., 2014[56]; Schilde et al., 2014[33]; 2015[57]; Braekers and Kovacs, 2016[45]; Masmoudi et al., 2016[58]; Detti et al., 2017[52]; Molenbruch et al., 2017[28]
	Genetic algorithms	Jorgensen et al. 2007[12]; Cubillos et al. 2009[59]; Núñez et al., 2014[60]; Muñoz-Carpintero et al., 2015[61]
	Hybrid algorithms	Parragh et al., 2009[62]; Chevrier et al., 2012[63]; Santos and Xavier, 2015[17]; Zhang et al., 2015[64]; Chassaing et al., 2016[65]; Masmoudi et al., 2016[58]; 2017[66]; Molenbruch et al., 2017[28]; Pimenta et al., 2017[16]; Lim et al., 2017[27]; Schönberger, 2017[67]
Simulation techniques	Simulation	Pei et al. 2019 [39]

(mainly composed of basic bus fare income and passengers' WTPs), bus operation costs, and passengers' time costs. The contributions of this paper are as follows:

First, we propose an FTS model based on the WTPs of heterogeneous passengers to meet their needs for various services. Moreover, their demand requests and willingness to pay are not fixed, and their WTP decreases as the walking distance increases.

Second, the selected B-level bus stop is cast into a 0-1 integer optimization and can be solved very fast under the combination of the enumeration method and tabu search method. The effective algorithm makes it feasible for real-world application.

Third, this paper provides a way for bus companies to estimate the income after transforming an existing bus line into a flexible bus line. It can help the decision-maker in planning and management.

The remainder of this paper is organized as follows: Section 2 expresses the methodology of the optimization model. Section 3 presents a numerical example based on No. 87 bus in Guangzhou, in which the existing line is replaced with a flexible bus line system. Section 4 discusses the sensitive parameters and operation selection strategies for bus companies. Section 5 concludes the paper.

II. METHODOLOGY

A. NOTATION

For the convenience of the readers, the critical notations used throughout the paper are summarized in TABLE 3.

TABLE 3. Notation.

Sets	
$\mathcal{A}$	Set of A-level bus stops, $\mathcal{A} = \{1,2,3,\ldots,n,\ldots,A\}$
$\mathcal{B}$	Set of B-level bus stops, $\mathcal{B} = \{1,2,3,\ldots,i,\ldots,B\}$
$\mathcal{B}_{n,n+1}$	Set of B-level bus stops between A-level bus stops n and $n+1$
$\mathcal{I}$	Set of select-visited B-level bus stops between A-level bus stop n and stop $n+1$, $\mathcal{I} = \{i \mid x_i = 1\}$
$\mathcal{K}$	Renumber the bus stops in set $\mathcal{I}$ according to the Dijkstra algorithm, $\mathcal{K} = \{1,2,\ldots k,\ldots,K\}, K = card(\mathcal{I})$
$\mathcal{U}$	Set of passengers. $\mathcal{U} = \{1,2,3,\ldots,u,\ldots,U\}$
$\mathcal{U}_i$	Set of passengers picked up at bus stop i
Parameters	
n	A-level bus stops, $n \in \mathcal{A}$
i	B-level bus stops, $i \in \mathcal{B}$
u	Index passenger, $u \in \mathcal{U}$
i'_u	Request pickup location for passenger u, $i'_u \in \mathcal{A} \cup \mathcal{B}$
t_u^1	Start departure time of passenger u
t_u^2	End departure time of passenger u
$P_{i'}^u$	WTP of passenger u at the request pickup location i'(Yuan)
i_u	Final pickup location of passenger u, $i_u \in \mathcal{A} \cup \mathcal{B}$
P_i^u	WTP for passenger u at the final pickup location i (Yuan)
n_u	Destination of passenger u, $n_u \in \mathcal{A}$
t_0	Departure time of bus shift at first A-level stop (index of a bus)
t_i	Arrival time at B-level bus stop i
t_n	Arrival time at A-level bus stop n
$d_{i,i'}$	Passenger walking distance from bus stop i to i'
$l_{i,j}$	Distance from bus stop i to j
Y_n	System income from a bus stop n to bus stop $n+1$ (Yuan)
Y_{line}	System income of whole bus line. (Yuan)
Y^0	System income of whole bus line for PTS (Yuan)
P_0	Base bus fare (Yuan)
θ	Bypass distance ratio
Q	Vehicle capacity
r	Rate of willingness to pay
P_i	Accumulated WTP value at bus stop i (Yuan)
$P_i^u(t)$	WTP for passenger u at bus stop i at time t (Yuan)
N_i	Number of passengers that board at bus stop i, $i \in \mathcal{K}$
$N_i^u(t_i)$	Passengers board on bus at bus stop i at time t_i, $i \in \mathcal{K}$
M_n	Number of passengers on the bus at A-level bus stop n
M_n^O	Number of passengers that board on bus at A-level bus stop n
M_n^D	Number of passengers that get off bus at A-level bus stop n
H_i	Number of passengers on the bus at B-level bus stop i
C_1	Unit operation cost (Yuan/km)
C_2	Time cost value of passenger on the bus (Yuan/km)
C_3	Total transformation fee of a whole bus line (Yuan)
C_4	Transformation fee of a single bus shift (Yuan)
$\Delta l_{n,n+1}$	Relative detour distance from A-level bus stop n to $n+1$ (km)
$\Delta l_{i,n+1}$	Relative detour distance from B-level bus stop i to $n+1$ (km)
v	Average speed (km/h)
Decision variables	
x_i	Binary variable: $x_i = 1$ if B-level bus stop i is selected visit; $x_i = 0$ otherwise.
X	$X = \{x_1, x_2 \ldots, x_I\}$

B. PROBLEM STATEMENT

Consider a set of A-level bus stops $\mathcal{A} = \{1, 2, 3, \ldots, n, \ldots, A\}$, which are mainly from the popular existing bus stops that have sufficient travel requests. Passengers can board and alight on these A-level bus stops because they are guaranteed to provide service. For specific A-level bus stops n and $n+1$, consider a set of B-level bus stops $B_{n,n+1}$ between A-level bus stops. These B-level bus stops are both from degraded existing bus stops and some potential requested locations. Since B-level bus stops are select-visited, they can only provide service for those boarding passengers. Consider a set of passengers $\mathcal{U}$, we assumed that all these passengers are making reservations right before their travel.

To be better understand the operation process of FTS, FIGURE 2 shows an example time sequence. For passenger $\boldsymbol{u}$, his/her reservation includes the requested pickup location $\boldsymbol{i'_u}$, destination $\boldsymbol{n_u}$, maximum WTP $\boldsymbol{P^u_{i'}}$, and departure time window $(\boldsymbol{t^1_u}, \boldsymbol{t^2_u})$. In this study, real-time orders can be priority-matched to the nearest bus that followed before bus stop $\boldsymbol{n}$, and the instant route will be selected from an A-level stop $\boldsymbol{n}$ to an A-level stop $\boldsymbol{n+1}$. The route plans are made from district to district; thus, passengers can make reservations before the district begins (the deadline for district $\mathcal{B}_{\boldsymbol{n,n+1}}$ should be time $\boldsymbol{t_n}$). The system average calculating time (AOT) $\boldsymbol{t'}$ is generally less than 3 seconds. Then, the flexible route and schedule are produced.

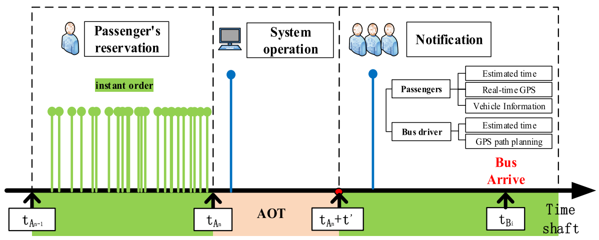

FIGURE 2. The time sequence of the flexible operation system.

Passengers receive notices with their service list, including the final pick-up station i_u as well as the estimated arrival time t_i, arrival bus station i *or* n, and final WTP P^u_i. Additionally, we assume passengers have sufficient funds and accept the automatic deduction from their account. Then, passengers should arrive before the start of the reservation time range and leave at the end of the reservation time range. Passengers can also obtain the real-time location of the bus and route schedule instantly.

To facilitate the model formulation, we introduce the following assumptions. The proposed FTS is assumed to have a standard travel speed v. Passengers are assumed *(i)* to make reservations right before their travel; *(ii)* to have sufficient funds and to accept the automatic deduction from their account.

C. PROBLEM FORMULATION

This model is formulated to select-visit B-level bus stops between bus stops n and $n+1$. The objective function formulated in Equation (1) aims to maximize the total system income Y_n, including three terms, the total ticket fare income $\sum_i P_i x_i$ minus the operation costs and passengers' time costs. Since the base costs of A-level bus stops are standard, we omitted the base costs of A-level lines for conciseness. Let C_1 be unit operation costs and let $\Delta l_{n,n+1}$ be the relative detour distance from A-level bus stops n to $n+1$. The operation costs are for deviation (i.e., the second term in Equation (1), $C_1 \Delta l_{n,n+1}$). Let C_2 be the time cost value for passengers on the bus, while the time costs (i.e., the third term in Equation (1), $C_2(\Delta l_{n,n+1}M_n + \sum_i \Delta l_{i,n+1}N_i)$ can be calculated in two parts. One part is the passengers on the bus at A-level bus stop n (i.e., M_n) multiplied by their relative detour distance $\Delta l_{n,n+1}$, and the other part is the passengers that board at bus stop i multiplied by their relative detour distance $\Delta l_{i,n+1}$.

$$\max_{x_i} Y_n = \sum_i P_i x_i - C_1 \Delta l_{n,n+1} - C_2(\Delta l_{n,n+1}M_n + \sum_i \Delta l_{i,n+1}N_i) \quad i \in \mathcal{B}_{n,n+1}, n \in \mathcal{A}\{A\} \quad (1)$$

1) WTP PREPARATIONS

We consider an exponential decay function $P = ce^{-\beta x}$ [1] to define the WTP in Equation (2). Let P_i^u denote the WTP of passenger u at the final pickup location i and let $P_{i'}^u$ denote the WTP of passenger u at the requested pickup location i'. For each passenger u, since her/his WTP is no less than the base ticket price (P_0), we can get her/his extra WTP $P_{i'}^u - P_0$. Then, the final WTP can be calculated by the decay exponential function. Let $d_{i,i'}$ denote the passenger walking distance from bus stop i to i', and β is a coefficient of the function.

$$P_i^u = P_0 + \left| \left(P_{i'}^u - P_0\right) e^{-\beta d_{i,i'}} \right| \quad i, i' \in \mathcal{A} \cup \mathcal{B}\ u \in U \quad (2)$$

2) SELECTIVE VISITS

For each B-level bus stop i, we calculate the ticket fare income (P_i) the bus company can gain according to the estimate time of bus (t_i) and the time window range of the reserved passengers, as stated in Equations (3) and (4). Equations (5) and (6) are used to count the number of passengers who board the bus at B-level bus station i. Equation (7) is used to calculate the number of passengers on the bus at bus stop i. Moreover, Equations (8), (9) and (10) count the number of passengers on the bus at A-level bus station n. We also define a mapper $i \leftrightarrow j$, which means $i \in \mathcal{A} \cup \mathcal{B}$ corresponds to the bus stop $j \in \mathcal{K}$ according to the definition of set $\mathcal{K}$.

$$P_i^u(t_i) = \begin{cases} P_i^u, & t_u^1 \le t_i \le t_u^2\ u \in \mathcal{U}, i \\ 0, & else\ \in \mathcal{A} \cup \mathcal{B} \end{cases} \quad (3)$$

$$P_i = \sum_{u \in \mathcal{U}_i} P_i^u(t_i) \quad i \in \mathcal{A} \cup \mathcal{B} \quad (4)$$

$$N_i^u(t_i) = \begin{cases} 1, & t_u^1 \le t_i \le t_u^2\ u \in \mathcal{U}, i \\ 0, & else\ \in \mathcal{A} \cup \mathcal{B} \end{cases} \quad (5)$$

$$N_i = \sum_{u \in \mathcal{U}_i} N_i^u(t_i) \quad i \in \mathcal{A} \cup \mathcal{B} \quad (6)$$

$$H_j = M_n + \sum_{k \le j} N_k \quad j \in \mathcal{K} \quad (7)$$

$$M_{n+1} = M_n + \sum_{i \in \mathcal{K}} N_i + M_{n+1}^O - M_{n+1}^D \quad n \in \mathcal{A}\backslash\{A\} \quad (8)$$

$$\Delta l_{n,n+1} = l_{n,1} + \sum_{k \in \mathcal{K}} l_{k,k+1} + l_{K,n+1} - l_{n,n+1} \quad n \in \mathcal{A}\backslash\{A\} \quad (9)$$

$$\Delta l_{j,n+1} = \sum_{k=j}^{K-1} l_{k,k+1} + l_{K,n+1} - l_{j,n+1} \quad j \in \mathcal{K},\ n \in \mathcal{A}\backslash\{A\} \quad (10)$$

3) TIME WINDOW CONSTRAINTS

The vehicle route should be legitimate, and each customer should be picked up before he/she is delivered. The arrival time t_i at bus stop i of the route should satisfy passengers' departure ranges, with the latest arrival times at the B-level bus stop t_i and the A-level bus stop t_{n+1}. For simplicity, the time needed for each customer to get on or off the vehicle is not taken into account in this study. Equation (11) shows the estimated arrival time of B-level bus stop i, and Equation (12) shows the dynamic time transfer function of A-level bus stop $n + 1$.

$$t_i = t_n + \frac{l_{n,1} + \sum_{k=1}^{j-1} l_{k,k+1}}{v} \quad i \in \mathcal{A} \cup \mathcal{B},\ j \in \mathcal{K},\ k \in \mathcal{K},\ n \in \mathcal{A}\backslash\{A\},\ i \leftrightarrow j \quad (11)$$

$$t_{n+1} = t_n + \frac{\Delta l_{n,n+1}}{v} n \in \mathcal{A}\backslash\{A\} \quad (12)$$

4) FEASIBILITY CONSIDERATIONS

We set specific limiting rules, such as a detour ratio limitation in Equation (13) and a restriction on the number of B-level stops between bus stops i and $i + 1$ in Equation (14), which can effectively limit the maximum ride time. Moreover, Equations (15) and (16) define the volume capacity of passengers on the bus.

$$\frac{\Delta l_{n,n+1}}{l_{n,n+1}} \le \theta \quad n \in \mathcal{A} \quad (13)$$

$$\sum_{i \in \mathcal{K}} x_i \le N \quad (14)$$

$$M_n \le Q \quad n \in \mathcal{A} \quad (15)$$

$$H_i \le Q \quad i \in \mathcal{K} \quad (16)$$

D. SOLUTION FRAMEWORK

In this study, the model is a 0-1 integer programming problem. We apply an advanced tabu search method together with the enumeration method to solve the problem. Within a single block from bus stop n to bus stop $n+1$, the number of B-level stops is limited. The number of categories increases with the number of B-level stops. When the number of bus stops is 12, the system calculation time is approximately 2.67 seconds in the traversing method, and when the number of bus stops is greater than 13, we can choose a tabu search (0.256 seconds for 20 bus stops). Thus, we choose the traversing method and tabu search according to the number of B-level stops and ensure that the real-time response model works smoothly. More details are shown in Algorithms 1, 2 and 3.

III. NUMERICAL EXAMPLE

A. EXPERIMENT DESCRIPTION AND PARAMETER SETTINGS

To test the effectiveness of the proposed select-visit FTS operation approach, the No. 87 bus line in Guangzhou is selected

Algorithm 1 General Approach

for each $n \in \mathcal{A}$, **do**
  count the number of B-level bus stops in $B_{n,n+1}$
  if length$B_{n,n+1} \leq 12$
    for each $x_i \in X$, **do**
      calculate objective function
    end for
  else
    use Algorithm 2,3
  end if
  calculate bus line cost Y_{line}
end for

Algorithm 2 Generate X_0

$X := 0^{1*B}$
for $N_B = 1:N$, **do**
  $x_{best} = x_1$ and $Y_{best} = 0$
  for each i in $B_{n,n+1}$, **do**
    if $x_i = 1$, **continue**
    else
      $\mathbf{X_{temp}} := \mathbf{X}$, $\mathbf{X_{temp}}\ (\boldsymbol{i}) = \mathbf{1}$
      if $Y_n\left(X_{temp}\right) > Y_{best}$
        $x_{best} := x_i$ and $Y_{best} := Y_n\left(X_{temp}\right)$
      end if
    end if
  end for
    $x_{best} := 1$
end for
$X_0 := X$

Algorithm 3 The Advanced Tabu Search Method

$X_{best} := X_0$ and $X_{now} := X_0$;
Set tabu list $Tlist = \{X_{now}\}$;
for $step := 1 : stepmax$
  $neighborhood := \{X_{now} | \mathbf{1}^{\mathrm{T}} * abs\,(X_{now} - X) = 1$ and $\mathbf{1}^{\mathrm{T}} * X_{now} \leq N$
  $Y_{now} := 0$
  $Flag := false$
  for each $neightbor$ **in** $neighborhood$
    if $Y_n\,(neighbor) > Y_{now}$ and $neighbor \notin Tlist$
      $X_{now} := neighbor; flag := true$
    end if
  end for
  if $flag = false$, break
  end if
  $Tlist$. push X_{now}
  if $Y_n\,(X_{now}) > Y_n(X_{best})$
    $X_{best} = X_{now}$
end if
if $Tlist$. size > max. Tabu size
    $Tlist$. remove first lines
end if
end for
return X_{best}

to perform the numerical experiments. The passenger demand data used in the experiments are obtained by the real-world operation of passenger-card data from March 2017. The parameter values are set as follows.

We focused on the off-peak hours and selected a total of 24 A-level stops and 138 potential B-level stops, as it states in FIGURE 3. Moreover, we obtained the real bus route distances and walking distances for the 162 bus stops and estimated the travel time between any two points using an average bus speed of 31.85 km/h. Since the FTS in this paper is not in the market, we generate the demand of the passengers and their origin WTPs according to the existing data. We simulated a total of 702 reservation requests between 10:00 a.m. and 12:00 p.m. Consistent with the initial research [9]–[12], the passengers' reservation simulation data appropriately reacted to the B-level stops.

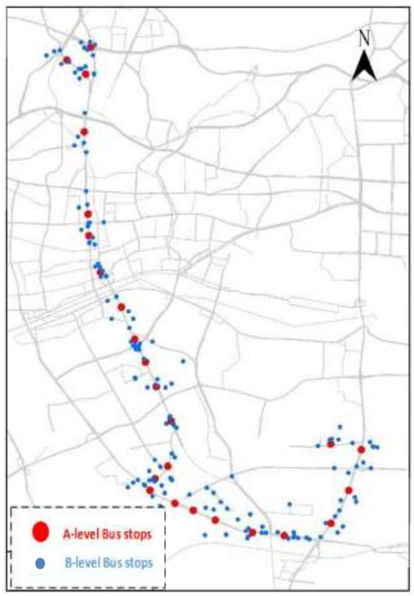

FIGURE 3. **A and potential B-level bus stops.**

B. SIMULATION PROCESS

There are 24 A-level stops on the line, and the bus lines are divided into 23 districts and are optimized for each district. The computer is equipped with an Intel(R) i7-7700 CPU and 16.0 GB RAM. The operating time of the precise algorithms is 2.823 seconds ($i = 12$), and that for the tabu search is 3.53 seconds ($i = 20$). Since this FTS model is formulated district to district-to-district, the select-visit B-level bus stops are solved step-by-step, as it states in TABLE 5. When the B-level bus stops between districts A1-A2 is optimal, the routing and estimate arrival time is decided in step 1. Then, by inputting the estimate time of A1 in the dynamic time transfer function Equation. (12), we get the departure time of A2 and continuously solve the FTS model in districts A2-A3, as it states in step 2. Finally, we get the

TABLE 4. Parameter settings.

Parameter	Value	Data source
A	24	Guangzhou No. 3 bus company (http://www.bus3.cn/sitecn/msg.aspx/)
B	158	Gaode map
P^0	¥2	Guangzhou No. 3 bus company (http://www.bus3.cn/sitecn/msg.aspx/)
C_1	1	Guangzhou No. 3 bus company (http://www.bus3.cn/sitecn/msg.aspx/)
C_2	0.25	Guangzhou Municipal Human Resources and Social Security Bureau reports (http://gzrsj.hrssgz.gov.cn/english/)
θ	3	We consider the maximum deviation distance.[2]–[5]
N	5	We consider the maximum on bus time and deviation distance.[3], [6]–[8]
Q	75	Guangzhou public transit report.
v	31.85 km/h	Operating speed of MV in city road. (http://www.gzjt.gov.cn/gzjt/jtzt_sjkf_jtysyb/201903/)

TABLE 5. Bus Schedule.

Solving steps	Estimate time	Bus stop	Passenger load	Boarding Passengers	Alighting Passengers
1	10:00	A1	3	3	0
	10:03	**B5**	5	2	-
2	10:08	A2	8	4	1
3	10:12	A3	6	1	3
4	10:18	A4	10	4	0
5	-	A5*	10	0	0
	10:20	**B25**	12	2	-
6	10:26	A6	11	1	0
	10:29	**B36**	13	2	-
7	10:35	A7	17	4	4
	10:36	**B48**	18	1	-
8	10:38	A8	19	6	5
9	10:43	A9	22	4	1
10	10:44	A10	27	7	2
11	10:47	A11	29	4	2
12	10:48	A12	29	5	5
13	10:52	A13	29	5	5
14	10:56	A14	29	3	3
15	10:58	A15	28	5	6
16	10:59	A16	29	4	3
17	11:03	A17	26	5	8
18	11:05	A18	24	3	5
19	11:06	A19	20	2	6
20	11:09	A20	17	3	6
21	11:15	A21	15	3	5
22	11:20	A22	11	1	5
23	11:21	A23	6	1	6
	11:24	A24	0	0	1

whole bus line optimal schedule in TABLE 5, which includes the estimate time of each bus stop, based on the bus passenger load, i.e., the number of boarding and alighting passengers.

Then, we marked the selected B-level bus stops on the map, as shown in FIGURE 4. In the A1-A2, A5-A6, A6-A7, and A7-A8 districts, there are passengers with a strong WTP and appropriate departure time windows, which makes them worth servicing; the system increases its income by ¥22.54, ¥20.354, ¥12.182, and ¥10.256 in these districts, respectively.

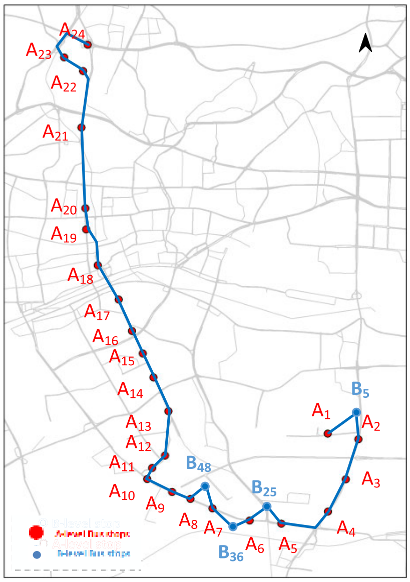

FIGURE 4. Optimal route of the whole bus line.

The whole bus line income Y_{line} denotes the summary of the bus districts income $Y_n, n \in \mathcal{A}\backslash\{A\}$. In this numerical example, the whole bus line income is ¥205.33.

$$Y_{line} = \sum_{n \in \mathcal{A}\backslash\{A\}} Y_n \tag{17}$$

C. RESULT COMPARISONS

To evaluate the proposed FTS, this section describes an existing benchmark system, the PTS, as shown in FIGURE 1.a. We see that the fare income and system income both increase dramatically (above 29%). The average waiting time passengers have saved is 8.25%. The number of passengers served on the bus has increased, and the maximum full load rate has increased by a percentage of 8.86% and 8.33%, respectively, when compared with the PTS. As for the service coverage, since it is usually designed to have a radium coverage of 300 meters, we also increased by using the B-level deviation bus stops.

IV. DISCUSSION

A. ECONOMIC ANALYSIS

We propose an FTS model that considers passengers' WTP, which follows the rule that passengers should be able to pay more beforehand for better service [9], [13]. With this model, both the full load rate and income of the bus company increase. Thus, the model changes the operating mode of the existing bus line and increases the total income of the system.

B. APPLICABILITY ANALYSIS

It is important to analyze when it is economical to transform an existing PTS to an FTS because the transformation process costs money. C_3 denotes the transformation -process cost, which includes information system research, development

TABLE 6. Comparison of the FTS with the PTS.

Index		PTS	FTS	Increase/Savings	Increase/Save rate
Income	Fare income	¥158	¥214	¥56	35.44%
	Deviation time cost	0	¥9.67	-	-
	System income	¥158	¥205.33	¥47.33	29.96%
Time saved	Average waiting time	4 min	3.67 min	0.33 min	8.25%
Service distance	Maximum full load rate	36%	39%	3%	8.33%
	Actual service number	79	86	7	8.86%
	Service coverage area (300 m)	5,220 m^2	15,660 m^2	10,440 m^2	200%

*Note: Number of lists = 702, $C_2 = 0.25$, $r = 1$, for bus departure time 10:00.

costs, system maintenance costs, staff training costs, passenger publicity costs, and social outside impact cost. We assume a cost recovery cycle and let C_4 denote the transformation costs per bus shift. Then, the system income of an FTS should be no less than the transformation costs, as stated in Equation (18)

$$Y_{line} - Y^0 \geq C_4 \tag{18}$$

Furthermore, we study the transformation costs and calculate the average costs of a bus shift to determine whether the transformation is needed. As reflected in the data in the Guangzhou transit report, the new flexible transit system should increase costs by approximately ¥26-¥35/bus line for software development, hardware transformation, staff training, and marketing. Thus, in this case, we set the transformation line at approximately ¥184-¥193.

Additionally, the percentage of B-level passengers compared to all passengers should be considered. We find that when the income Y_{line} is ¥320-¥330, the number of requests from 10:00 to 12:00 is approximately 2000, which is almost three times the number of existing bus passengers. A high percentage of requests indicates that the existing bus line is inappropriate and needs to be re-planned. In this case, we set the re-planned line at approximately ¥320-¥330. Thus, in this paper, we choose the mode of public transport according to the final bus line income and analyze the following parameters: the number of reservation lists and the values of the parameters C_2 (time costs of the passengers on the bus) and r (WTP intensity).

1) NUMBER OF RESERVED PASSENGERS U

We study the sensitivity of the results to different degrees of demand variability. FIGURE 5 shows how the number of B-level stops on passengers' reservation lists affects the bus line revenues. Additionally, by performing a regression analysis of Y_{line} with the number of reserved passengers, we obtain Equation (19).

$$Y_{line} = 115.893 + 0.10286U \tag{19}$$

In this regression analysis, the sample size is relatively small (only 40 samples), which causes larger volatility.

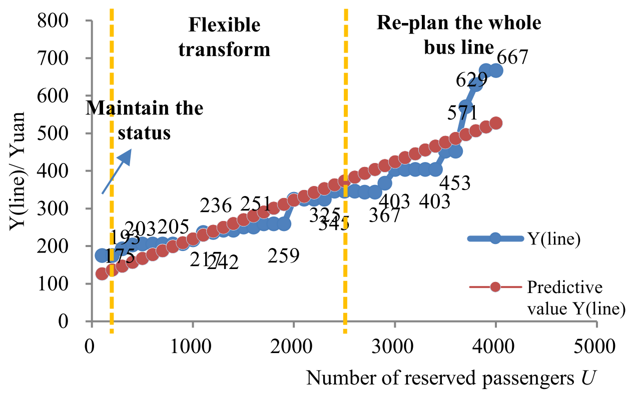

FIGURE 5. Bus line income with reservations.

However, the plot still shows good linearity. R-squared is 0.8449, which can better reflect the appropriate characteristics. The coefficient of the number of reservation lists is 0.10286, which means that for every additional order, the line revenue Y_{line} increases by ¥0.10. This conclusion can be used to give a rough estimate of the expected return after the flexible transformation of the bus lines. Orders of different quantities can be generated at random, and multiple simulations should yield a higher coefficient of fit, which could provide further improvements.

2) PARAMETER C_2 AND WTP RATE r

We vary the parameter C_2 (time cost of the passengers on the bus) from 0 to 1 in increments of 0.05, and we vary the coefficient of variation r (WTP rate) from 0 to 3 in increments of 0.1. The coefficient of variation depends on many factors, such as the purpose of the trip. For instance, if a bus route mainly serves people commuting to/from work, then the value of the parameter C_2 is larger. If a bus route mainly serves people going to a park, then the value parameter C_2 is much smaller. Furthermore, on a rainy day, more people will take the bus, and they may have a stronger WTP (the value of r is strong). We report the results in TABLE 7.

In this regression analysis, the sample shows excellent linearity. The R-squared is 0.9096, which can better reflect the appropriate characteristics. From fitting the above data,

TABLE 7. The value of the bus line with parameter C_2 and WTP rate r.

r \ C_2	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1
0	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158
0.1	160	159	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158
0.2	163	165	163	162	160	159	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158
0.3	172	166	163	161	159	164	163	162	160	159	158	158	158	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	158	158	158
0.4	184	175	170	166	164	162	160	159	158	164	163	161	160	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	158	158	158
0.5	196	183	178	173	169	167	165	163	161	160	159	159	166	164	163	161	160	158	158	158	158
0.6	209	193	187	182	177	173	170	168	166	164	162	161	160	160	159	159	165	164	162	161	159
0.7	221	202	195	190	185	181	177	173	171	169	167	165	163	162	162	161	160	160	159	158	165
0.8	236	211	204	199	193	188	184	180	176	174	172	170	168	166	164	163	163	162	161	161	160
0.9	251	221	213	207	202	197	192	188	184	180	178	176	174	172	170	168	166	164	164	163	163
1	260	236	222	216	210	**205**	200	195	191	187	184	181	179	177	175	173	171	169	167	166	165
1.1	274	248	232	224	219	214	209	204	199	195	191	187	184	182	180	178	176	174	172	170	168
1.2	287	261	241	233	227	222	217	212	207	202	199	195	191	187	185	183	181	179	177	175	173
1.3	306	273	250	243	236	231	226	221	215	210	206	202	198	194	191	188	186	184	182	180	178
1.4	320	285	260	252	244	239	234	229	224	219	214	210	206	202	198	194	192	189	187	185	183
1.5	335	298	270	261	254	248	243	238	232	227	222	217	213	209	206	202	198	195	193	191	189
1.6	349	317	288	271	263	256	251	246	241	236	231	225	221	217	213	209	205	201	198	196	194
1.7	364	331	300	280	272	265	260	255	249	244	239	234	229	224	221	217	213	209	205	201	199
1.8	378	345	312	289	282	274	268	263	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	228	224	220	216	212	209	205
1.9	392	360	325	299	291	283	277	272	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	241	236	232	228	224	220	216	212
2	407	374	337	309	300	293	285	280	275	270	265	259	254	249	244	239	235	231	227	224	220
2.1	421	388	350	327	310	302	294	289	283	278	273	268	263	258	252	247	243	239	235	231	227
2.2	436	402	362	339	319	311	304	297	292	287	282	276	271	266	261	256	251	246	242	239	235
2.3	450	416	383	352	329	321	313	306	300	295	290	285	280	275	269	264	259	254	250	246	242
2.4	464	415	398	364	338	330	322	315	309	304	299	293	288	283	278	273	268	263	257	254	250
2.5	479	428	412	377	348	339	332	324	317	312	307	302	297	292	286	281	276	271	266	261	257
2.6	558	442	426	389	358	348	341	333	326	321	316	310	305	300	295	290	285	280	274	269	265
2.7	574	455	440	401	379	358	350	343	335	329	324	319	314	309	303	298	293	288	283	278	273
2.8	591	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	352	344	338	333	327	322	317	312	307	302	297	291	286	281
2.9	608	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	361	354	346	341	336	331	326	320	315	310	305	300	295	290
3	625	509	483	439	416	387	378	371	363	355	350	344	339	334	329	324	319	314	308	303	298

Maintain the status

Flexible transformation

Re-plan the whole bus line

Note : (Number of lists = 702, start time = 10:00).

Equation (20) is obtained:

$$Y_{line} = -95.3731C_2+74.8383r+173.7347 \qquad (20)$$

In Equation (20), Y_{line} has a linear relationship with C_2 and r. The time cost changes from city to city and the system income will inevitably decrease as the unit time cost increases. Parameter r is the rate of the passengers' WTP. It is worth emphasizing that the WTP of the passengers has robust individual heterogeneity and is affected by many factors, such as the level of the urban economy, residents' income, ride difficulty, ride distance, waiting time, ride comfort, and vehicle operation mode. The most straightforward way to accurately assess the WTP of passengers is to take samples from passengers (especially from flexible public transit passengers who have already paid) and to guide the transformation of other bus routes. In this case, parameter r means multiplying by a different intensity factor based on the WTP for the existing sample order. Y_{line} is not strictly linear with the passengers' WTP in a single reservation order but is linear with the WTP for selected bus stops within the time window. Therefore, Y_{line} and the order of the WTP willingness coefficient parameter r form a better relationship. Additionally, because the program is discrete and inconsistent, the value of the WTP can also spike. Therefore, the value of R-squared is 0.90, which can respond to the linear relationship.

V. CONCLUSION

This paper proposes a real-time FTS model that allows passengers to make individual demand requests and get customized door-to-door service. To enable practical application, we combined the traversing method and the improved tabu search algorithm to solve this model as accurately and as fast as possible. The model can satisfy passengers with different departure stops and time window requirements and optimize the route and schedules. Adapting to their higher-income passengers' wishes can bring better benefits to the bus company. The numerical example from Guangzhou shows that the system income can improve by ¥47.33 (29.96%) for a single bus shift at the scale of 702 reservation orders.

Moreover, the conclusion of the model is instructive to bus companies. Bus companies can learn from the data whether commuter passengers are apparent, whether the number of passenger orders is adequate, the percentage of flexible transit passengers, and the intensity of the passengers' WTP, among others. This conclusion can provide a rough estimation for the bus company and estimate the increased income with flexible transformation. Then, it can help decision-makers determine an appropriate time point to choose various operation modes.

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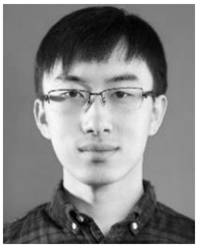

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