Coordination of Last Train Transfers using Potential Passenger Demand from Public Transport Modes

Wei Li1,2, Qin Luo1, Qin Cai3
1College of Urban Transportation and Logistics, Shenzhen Technology University, Lantian Road 3002, Shenzhen, 518060, China
2Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen, 518060, China
3Department of Civil, Environment and Construction Engineering, University of Central Florida, Orlando, Florida 32816, USA

Corresponding author: Qin Luo (e-mail: 465312799@qq.com).

ABSTRACT Metro trains stop operation during midnight for the maintenance of vehicles and tracks in most cities, where passengers heavily rely on the metro for their daily life. Thus, passengers may miss the last trains when they travel by metro at late night. However, the last trains are especially important because they are the last chances for many passengers to travel by metro. If passengers miss the last trains, they have to choose buses, taxies, or other transport modes to complete their trips. Consequently, it is necessary to optimize the schedule of the last train coordination to meet the demand of passengers at transfer stations during midnight. The passenger demand for last trains is a vital input to deal with the coordination of last train transfers. This paper focuses on forecasting the potential passenger demand of last trains from public transport data including taxi (FCD data) and bus (GPS/smart data) systems. A solution for taxi and bus data is developed to calculate the potential passenger demand for all the transfer directions of the target stations. Then, a model for the coordination of last train transfers based on the potential passenger demand is proposed. The genetic algorithm is applied to solve the model. The effectiveness of the proposed method is evaluated using the Shenzhen metro network with several data on a typical Friday. The research is to provide theoretical guidance and technical reference for the metro operation when to compile the last train schedule. It is supposed to improve the modern operation management level of metro systems.

INDEX TERMS Public transportation, metro, last trains, transfer coordination, potential passenger demand

I. INTRODUCTION
Metro system is a kind of transportation system with the advantages of large capacity, rapidness, punctuality and comfort, which can effectively solve many problems such as high population density, large traffic jam, and road congestion in large cities. With the gradual acceleration of metro planning, construction and operation, the metro system in urban transport modes is becoming more and more important. At present, some big cities in China such as Beijing, Shanghai, and Shenzhen have entered the stage of network operation, which the metro operation should consider the transfer coordination among lines in the network. One of the core issues in metro network operation is how to ensure the optimal transfer of metro transit lines, especially the effective coordination of last trains as metro trains stop operation during midnight. For passengers, the transfer coordination during the regular time would only affect their waiting time when they transfer. However, the last trains are especially important because they are the last chances for many passengers to travel by metro—as opposed to taxi or other modes that may be more costly and take more time, as shown in Figure 1. The taxi cost is much higher than the metro and bus, especially during midnight. It has 30% extra fee to ride a taxi comparing to regular time in some Chinese cities. Meanwhile, the time spending of the bus is averagely twice that of the metro, as seen in Figure 2.

FIGURE 1. Incoordination of last trains for passenger transfers
Passengers may miss the last trains in transfer stations after they have an interchange between two lines due to the incoordination. Taking a station of Shenzhen Metro (Baoan Center) as an example, the outbound passenger flow of the station shows a sudden peak at the end of the metro operation period, as shown in Figure 3. The sudden passenger flow contains not only normal outbound passengers but also the passengers who fail to catch up the last trains after transfer. Through further data analysis, the sudden outbound flow appears after the last train of the target transfer line leaves the platform. The occurrence of last train incoordination problem may not only waste passengers’ travel time but also affect their travel satisfaction, thereby reducing the level of metro service and potentially discouraging travelers from using the metro during midnight. With the continuous expansion of metro networks, the situation of poor transfer and incoordination of last trains will become more and more frequent. Consequently, it is necessary to optimize the adjustment of the last train coordination to meet the demand of passengers at transfer stations during the last train period. Here, the last train period is defined as the period when last trains run on networks prior to ceasing service at the end of the day. In the case of the Shenzhen metro, the last train period occurs between 22:00 – 24:00 daily and can affect more than 50,000 traveling passengers.

However, the complex and diverse structure of metro networks and the unknown passenger demand for the last trains are the main difficulties faced by the current metro operation when to optimize the coordination of last train transfers. At present, the AFC (Automatic Fare Collection) system used in most metro systems can only record passenger’s inbound and outbound information. The system cannot record passengers’ travel trajectories after they exit the metro. For the lack of passenger information when choosing other transport modes, it is impossible to accurately predict the potential travel demand for last train transfers. However, it is worth noting that in recent years that new technologies and equipment in urban traffic system have been put into use continuously, and abundant data resources have been accumulated in the process of operation and management, such as GPS data (Global Positioning System Data), smart card (Integrated Circuit Card) swipe data recorded by bus transit system, FCD data (Floating Car Data, Floating Vehicle Data) recorded by taxi transit system. These accumulating data have been reaching a huge amount over time as a big data, which can be used to calculate the potential passenger demand for last trains.

We apply the data analysis in the same station (Baoan Center) as an example, in which a large number of public transport data near the station over the whole day are screened and analyzed. It is found that after the regular metro operation time, a small peak in passenger flow can be observed in both taxi and bus trips, as shown in Figure 4. The left part of the figure shows the number of taxi riders near the station, while the right part shows the number of bus riders who swipe cards to board near the station. Further analysis shows that most passengers continue to reach the stations along the metro line by bus or taxi to complete their interruption trips. These data are not only the real travel demand of passengers at night but also the passenger demand about the last train transfers. In other words, this data can be regarded as the passengers who fail to ride the last trains after transferring. It can be used as data support to supplement the lost information of the metro trip chain in AFC card swipe data for last train transfers.
To sum up, in order to study the coordination of last train transfers in metro system, this paper mainly selects diversified public transport data resources to analyze and predict the potential passenger demand for last train transfers, including AFC data and train operation data of metro system, GPS data and smart card swipe data of bus system, FCD data of taxi system. Then, a demand-oriented coordination model for last train transfers is established to maximum the number of passengers who can successfully transfer to the last trains. The research project is to provide theoretical guidance and technical reference for the metro operation when to compile the last train schedule. It is supposed to improve the modern operation management level of metro systems.

II. LITERATURE REVIEW

Metro systems are not only the main mode of city transport but also provide important supports for city operations. They are developed rapidly in major cities of China with intractable heavy passenger loading during peak hours. Many studies focused on the metro daily management and operation with mass passenger flow and train delays, such as the vulnerability analysis of metro network and station[1,2], performance assessment of metro networks under various disruption scenarios[3] and train operation adjustment for relieving metro congestion[4].

However, among metro daily management and operation, the last train transfers play a key role in operating the metro system. Recently, various studies have attempted to address the issue of last train coordination problem and last train passenger demand problem. Among them, the coordination of last train transfers is based on the passenger demand for last trains.

In terms of the sources of last train passenger demand in the metro system, most of the studies are carried out with the optimization of last train schedules [5]. The theoretical methods of last train coordination and the sources of passenger flow demand used in current domestic and foreign studies are various. Table I compares some theoretical methods and the corresponding sources of passenger demand used in the studies. Few studies considered actual passenger demand during the last train period. Some research studied the last train problem without the consideration of passenger demand [5-8, 14-15], while others [9–12, 16-17] assumed that the demand is given or generated randomly. But the assumption might not be suitable because the hypothetical demand used may lead to completely different results compared to realistic situations. The prediction of passenger demand for last trains [13] is also not suitable since the passenger demand for last trains is difficult to forecast in such a large metro network. Besides, Li et al. [12] applied actual arrivals and OD pairs from AFC system data as the passenger demand data of last trains. However, they still didn’t consider the potential passenger demand.

### TABLE I

<table>
<thead>
<tr>
<th>Categories</th>
<th>Source of last train transfers flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize the waiting time of passenger</td>
<td>No consideration of passenger flow</td>
</tr>
<tr>
<td>Kang and Wu et al. [6]</td>
<td>No consideration of passenger flow</td>
</tr>
<tr>
<td>Kang and Meng [7]</td>
<td>No consideration of passenger flow</td>
</tr>
</tbody>
</table>

| Kang and Zhu et al. [5]    | improves the efficiency of transferring passengers |
|                           | running time and dwelling time |
|                           | genetic simulated annealing (GSA) algorithm |
|                           | maximize last train connections and minimize transfer waiting time |
|                           | original line departure time, running time and dwell time |
|                           | genetic algorithm (GA) |
| Kang and Meng [7]         | minimize the total transfer connection time for last train passengers, |
|                           | last train departure time |
|                           | branch-and-bound algorithm invoked by CPLEX |
### Kang and Zhu [8]
- Minimize the standard deviation of transfer redundant times
- Last train departure times, running times, and dwell times.
- Heuristic algorithm

### Chen and Mao et al. [9]
- Improve the transfer accessibility of urban rail networks
- Original line departure time, running time and dwell time
- Embedded Branch & Cut algorithm

### Maximize the passenger destination accessibility
- Yao et al. [11]
  - Last train departure time
  - Genetic algorithm
  - Maximize the dynamic accessibility index of urban rail transit
- Zhou et al. [12]
  - Last train departure time
  - Genetic algorithm
  - Improved passenger accessibility for last trains.
- Li and Xu et al. [13]
  - Last train departure time
  - Genetic algorithm
  - Maximize passengers who can reach their final destinations

### Ensure more passengers successful transfer
- Duo and Guo [14]
  - Minimize the number of transfer failures
  - Original line departure time, running time and dwell time
  - Commercial optimization solvers
- Kang and Wu [15]
  - Maximize network transfer accessibility (NTA)
  - Original line departure time, running time and dwell time
  - Genetic algorithm
- Yang et al. [16,17]
  - Maximize the number of successful passengers for transfer
  - Original line departure time, running time and dwell time
  - Tabu Search Algorithm
  - Optimize the connection scheme of the last trains
- Xu et al. [18]
  - Last train departure time
  - Kruskal algorithm

In terms of the coordination of last train transfers in metro systems, the existing literature mainly focuses on three aspects: minimize the waiting time of passengers, maximize the passenger destination accessibility, and ensure more passengers successful transfer. The first one takes arrival and departure time as variables, establishes an optimization model of last train transfers and designs an algorithm to solve the problem [19-21]. Other methods calculate the transfer redundant time and waiting time, and then build the optimization model of last train transfers [5-8, 22]. However, because the passenger flow in the last train period is smaller than that in the regular period, the waiting time for transfers is not as important as the destination accessibility or success rate of transfers. Some researches focused on the passenger destination accessibility for metro last trains. The destination accessibility indicates the percentage of passengers using last trains at origins who can reach their destinations successfully [9,10]. Yao [11] put forward a dynamic accessibility index of urban rail transit to optimize the last train schedule. Zhou [12] proposed a method to improve passenger accessibility for last trains by reducing transfer waiting time. Thirdly, other scholars put forward a cooperative transfer method to minimize the number of successful transfer directions or successful transfer passengers. By adjusting the arrival and departure time of the last train between two transfer lines, the trains on different lines can synchronously reach the same transfer station [14, 23-29]. In addition, some scholars have carried out research on the optimization of last train transfers with the goal of maximizing the number of successful transfer passengers [30]. The problem of the last train with train delays caused by incidents that occurred in train operations has also been discussed [31]. With the consideration of the coupling between different transportation modes, some articles also address the last train timetable optimization and bus bridging service problem in the context of urban railway transit networks [15].

In summary, the existing literature has less consideration on the demand of the last trains, and so it is necessary to carry out the theoretical research of passenger demand for last train transfers and the optimization of last train coordination, which is oriented to have practical application and high applicability and accuracy for the metro operation. This paper aims to estimate the potential passenger demand for last train transfers, which is fundamental to the last train coordination problem. The main contributions of this paper are listed as follows.

1. A new method to analyze and predict the potential passenger demand for last train transfers from diversified public transport data resources (bus, taxi, and other data);
2. The coordination of last train transfers by taking last train departure time from original stations as decision variables is carried out based on the potential passenger demand;
3. We apply GA as the solution algorithm to solve the proposed model, and Shenzhen metro network as case study to evaluate the effectiveness of the proposed method.
III. METHODOLOGY

A. BASIC RESEARCH FRAMEWORK

Making full use of the available multi-transport mode data resources under the existing equipment and technical conditions, this paper combines qualitative analysis and quantitative calculation, theoretical modeling and computer solution to study the predict method of potential passenger flow demand for last train transfers. Then an optimization model of last train coordination is constructed to improve the level of metro operation. Here, the predict method of potential passenger flow is the researching content 1, and the optimization method of last train coordination is the researching content 2, as seen in Figure 5.

![Figure 5: Research framework of the proposed method](image)

B. POTENTIAL PASSENGER DEMAND FROM PUBLIC TRANSPORT MODES

In the last train period, if metro passengers are not able to catch the last trains after transfers, they have to exit the station and transfer to other transport modes, such as bus and taxi, to continue to complete their trips. Therefore, urban public transport data resources can provide an idea for the speculation of the potential passenger demand for last train transfers.

It should be noted that the missing passengers due to failed transfer from the regular transferring are not distinguished. The estimation method proposed in the manuscript is to calculate the potential passenger demand for metro last trains. It is assumed that most passengers prefer to choose metro if the last train transfers are coordinated due to the metro’s advantages of large capacity, rapidness, punctuality, and comfort. Thus we regard all missing passengers as potential passenger demand for metro last trains.

To facilitate the presentation of the essential ideas without loss of generality, the following basic assumptions are made in this study:

a) Passengers are assumed to exit the station directly during the last train period without lingering or engage in non-travel activities (i.e. purchasing coffee, etc.).

b) One taxi traffic data record is regarded as single person travel, that is to say, two or more passengers share the same taxi is not considered. Since passengers ride the taxi will not charge extra money in some Chinese cities, the taxi traffic data do not contain such information.

c) Smart card holders are assumed as commuters or regular public transit passengers so that their enter stations (bus or metro) of next trip can be regarded as the exit stations of this trip.

d) The change of passenger capacity caused by the scheduling adjustment of the last train is not considered since the passenger flow in the last train period is much smaller than that in the regular period.

e) The passengers transfer to sharing bicycle and walk due to incoordination are not considered because the ratio for the cyclists and pedestrians due to incoordination is small, especially during the last train period.

1) PASSENGERS TRANSFER TO BUS DUE TO INCOORDINATION

For the passengers who fail to catch the last trains and transfer to buses, their trips can be linked as both trip chains leave travel information through smart card swiping data, as shown in Figure 6.

![Figure 6: Potential passenger flow transferring to the bus due to incoordination of last trains](image)
The principle for calculating potential passenger demand using bus traffic data is to connect the former metro travel trajectory and the latter bus travel trajectory by matching the smart card number. The union travel trajectory could be considered as the potential passenger demand. There are three key points to realize the calculation: fixing the alighting records for bus traffic, determining whether the data belong to potential metro demand, and linking these two travel trajectories.

The structure of the bus traffic data matrix is shown in Table II. The main useful items in the bus data are system time and its GPS location. However, these data must be used with smart card transaction data shown in Table III. Combining the two data, we could get the location (Longitude and Latitude) where passengers swipe their cards.

<table>
<thead>
<tr>
<th>System Time</th>
<th>Plate No.</th>
<th>Bus Line</th>
<th>GPS</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018-03-06T00:00:2600Z</td>
<td>BN4439</td>
<td>08120</td>
<td>114.304001</td>
<td>22.672001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transaction No.</th>
<th>Swiping Time</th>
<th>CardID</th>
<th>SwipingDeviceID</th>
<th>Fee</th>
<th>Plate No.</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>7022302</td>
<td>2018-03-06T00:00:2600Z</td>
<td>281199535</td>
<td>220002754</td>
<td>1.6</td>
<td>BN4439</td>
<td>...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>StationID</th>
<th>StationName</th>
<th>BelongingLineNo.</th>
<th>StationType</th>
<th>Longitude</th>
<th>Latitude</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>JiChangDong</td>
<td>01</td>
<td>1</td>
<td>113.8227187</td>
<td>22.64705293</td>
<td>...</td>
</tr>
</tbody>
</table>

With the obtained locations, we could determine whether they are close to the target transfer station or close to the stations in metro lines after comparing them with the longitude and latitude of the metro station location, as shown in Table IV.

In the end, we could link the bus travel trajectory with the metro travel trajectory according to the smart card number (CardID in both Bus and Metro smart card transaction data) in Table V. In summary, the potential passenger demand from bus traffic data can be obtained by these four kinds of data.

<table>
<thead>
<tr>
<th>SwipingDate</th>
<th>CardID</th>
<th>EnterTime</th>
<th>EnterStation</th>
<th>ExitTime</th>
<th>ExitStation</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>20180306</td>
<td>281199535</td>
<td>23:01:36</td>
<td>0132</td>
<td>23:25:44</td>
<td>0221</td>
<td>...</td>
</tr>
</tbody>
</table>

Since the bus data don’t contain the records where passengers swipe out of the bus, it is difficult to get the final destination of bus passengers. The common solution is to regard the passenger’s next boarding location (either bus or metro) as the exit location of this travel. That is to say, the boarding location of the next day’s trip is regarded as the alighting location of this late night trip.

Indeed, we do not distinguish the lost passengers due to failed transfer from the regular transferring. The estimation method proposed in the manuscript is to calculate the potential passenger demand for metro last trains. It is assumed that most passengers prefer to choose metro if the last train transfers are coordinated due to the metro’s advantages of large capacity, rapidness, punctuality and comfort. Thus we regard all lost passengers as the potential passenger demand for metro last trains.

The detailed algorithm (Algorithm 1) is shown in Figure 7.
Get the last train period from train timetable

Outbound passenger flow at the transfer station during the last train period

Match smart card number

Passenger transfer to the bus due to incoordination

Match bus alighting station and metro station

Passengers with potential transfer needs

Determine the possible metro demand based on the actual origin and the speculative destination

Potential passenger demand for metro

FIGURE 7 The flowchart of matching bus and metro passenger flow

2) PASSENGERS TRANSFER TO TAXI DUE TO INCOORDINATION

Through an investigation, it is found that the passengers who fail to transfer and exit to choose taxis account for a large proportion of the total demand. However, because there is no follow-up card swiping behavior in taxis, the taxi travel trajectory is relatively independent of the metro travel trajectory, as shown in Figure 8.

The principle for calculating potential passenger demand using taxi traffic data is to calculate the taxi travel volume after last train incoordination and to assign them according to the experience ratio of metro travel directions. There are two key points to realize the calculation: obtaining the taxi traffic volume due to failed transfers and ratio calculation.

The structure of taxi FCD (floating car data) is shown Table VI. The operational status in the table represent whether the taxi is on service, 1 is on service while 0 is free. The operational status changing from 0 to 1 means passengers boarding the taxi and the taxi is on service. The operational status changing from 1 to 0 represents passengers alighting the taxi. Thus we could match the taxi traffic data to metro stations by comparing the longitude and latitude in the two data. The taxi OD travel matrix is filtered to obtain the data whose origin is within the range of the transfer station and destination is close to the metro line.

<table>
<thead>
<tr>
<th>GPSDate</th>
<th>GPSTime</th>
<th>PlateNo.</th>
<th>Longitude</th>
<th>Latitude</th>
<th>OperationalStatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018-03-06</td>
<td>00:00:2600Z</td>
<td>B7HY30</td>
<td>114.093803</td>
<td>22.572033</td>
<td>0</td>
</tr>
<tr>
<td>2018-03-06</td>
<td>00:10:2000Z</td>
<td>B7HY30</td>
<td>114.099903</td>
<td>22.550618</td>
<td>1</td>
</tr>
<tr>
<td>2018-03-06</td>
<td>00:11:2600Z</td>
<td>B7HY30</td>
<td>114.000071</td>
<td>22.518415</td>
<td>1</td>
</tr>
<tr>
<td>2018-03-06</td>
<td>00:25:3200Z</td>
<td>B7HY30</td>
<td>113.940933</td>
<td>22.683567</td>
<td>0</td>
</tr>
</tbody>
</table>

FIGURE 8 Potential passenger flow transferring to taxi due to incoordination of last trains
The ratio in “Ratio Calculation” is the distribution rate of passenger flow from one metro line to another metro line in the target transfer station during a certain period. We could obtain the passenger demand from taxi traffic data, but we still do not know the passengers’ travel trajectory during their metro trips. Here, the step of “ratio calculation” is used to speculate their original paths in the metro network. For example, the target transfer station contains two metro lines, A and B. The taxi traffic data show that there are several passengers traveling from the target transfer station to some stations in the upstream of line B. Then we should speculate the number of passengers coming from both the upstream and the downstream of line A. The ratio is used to calculate them. After the analysis of historical data, we find the ratio of passengers from one direction of line B to two directions of line A changes a little during a short period (last train period in this manuscript), as shown in Figure 9. Hence, in the estimation method, we analyze historical passenger flow data to calculate the ratio for the potential passenger demand.

The detailed algorithm (Algorithm 2) is shown in Figure 9.

3) COMBINING ALL TRANSPORT DATA TO OBTAIN THE POTENTIAL PASSENGER DEMAND

In summary, the above algorithms make a full use of the external multi-source transport data during the last train period. The proposed method carries out a matching calculation for taxi and bus, then the potential passenger flow is obtained in all directions of each line at the transfer station. Also, the passenger flow of last trains contains not only the passengers who fail to board the last trains but also the passengers who succeed to board the last trains. The data acquired from metro AFC data (smart card data in metro) should be considered in the potential passenger demand. Thus all traffic data concluding the passenger flow from metro data, taxi data and bus data are combined to obtain a total potential passenger demand for last train transfers.

C. COORDINATION OF LAST TRAIN TRANSFERS

1) ASSUMPTIONS
   Before we model the coordination of last train transfers, the following assumptions have been made:
   a) The transfer time between different lines is assumed to know when passengers have interchange in transfer stations. The transfer time is obtained through investigation.
   b) The train section running time and station dwell time of last trains are known according to the train schedule, regardless of the delay time when it occurs.
   c) The passenger demand is fixed in the study period, and it will not change with the optimization of the train schedule.

2) CONSTRAINTS
   1) Constraint of last train transfers
      The symbols used in the proposed method are shown in Figure 10. Let \( l \) be the metro line, \( i,j \) be the indexes of the line, and \( g,h \) be the directions of the line. Besides, let \( S \) be the station list, \( S_k \) be the station and \( S_m \) be the transfer station, where \( k \) and \( m \) are the indexes of the station. \( S_m \) is the transfer station containing line \( l_i \) and \( l_j \) in the figure.
Successful transfer of last trains during the last train period should satisfy the condition \( \delta_{i,t,j}^{uw} = 1 \), if passengers from the last train of line \( l_i^g \) could board the last train of line \( l_j^h \) before the train depart the platform. Otherwise, \( \delta_{i,t,j}^{uw} = 0 \), as seen in Equation (1). Thus \( \delta_{i,t,j}^{uw} \) is the 0-1 variable.

\[
\delta_{i,t,j}^{uw} = \begin{cases} 
1 & T_{i,t,j}^r > 0 \\
0 & T_{i,t,j}^r < 0 
\end{cases} 
\]  

where \( \delta_{i,t,j}^{uw} \) is the indicator of successful transfer at station \( S_m \) from line \( l_i^g \) to line \( l_j^h \).

The successful transfer requires there should be allowed time for passengers transfer while taking into account the transfer walking time at station \( S_m \). The equation is expressed as below.

\[
T^{}_{i,t,j} = OT_{i,t,j}^{sw} - AT_{i,t,j}^{sw} - WT_{i,t,j}^{sw} 
\]  

where \( T^{}_{i,t,j} \) is the allowed time for passengers from line \( l_i^g \) to line \( l_j^h \); \( OT_{i,t,j}^{sw} \) is the departure time of the last train in line \( l_i^g \) at station \( S_m \); \( AT_{i,t,j}^{sw} \) is the arrival time of the last train in line \( l_j^h \) at station \( S_m \); \( WT_{i,t,j}^{sw} \) is the transfer walking time from line \( l_i^g \) to line \( l_j^h \).

(2) the constraint of running time and dwell time

According to the train schedule, the arrival time of the last train can be deduced by the departure time from the original station, train section running time and station dwell time.

\[
AT_{i,t,j}^{sw} = DT_{i,t}^{sw} + \sum_{k: s_k \rightarrow s_{k+1}} T^R_{s_k \rightarrow s_{k+1}} + \sum_{k: s_k \rightarrow s_{k+1}} T^m_{s_k} 
\]  

where \( DT_{i,t}^{sw} \) is the departure time of the last train in line \( l_i^g \), and \( DT_{i,t}^{sw} \) is the integer independent variable in this model; \( T^m_{s_k} \) is the station dwell time of the last train at station \( S_k \); \( T^R_{s_k \rightarrow s_{k+1}} \) is the section running time of the last train from station \( S_k \) to station \( S_{k+1} \).

The departure time of the last train can also be calculated by the formula (4).

\[
OT_{i,t,j}^{sw} = AT_{i,t,j}^{sw} + T^m_{s_k} 
\]  

(3) the constraint of last train departure from the original station

The operation of the last train should meet not only the passenger demand but also the operation cost and the time for maintenance of metro trains. Therefore, the departure time of the last train is also constrained by the departure conditions as shown in (5) and (6).

\[
DT_{i,t}^{sw} \leq DT_{i,t}^{max} 
\]

\[
DT_{i,t}^{sw} \geq DT_{i,t}^{min} 
\]

where \( DT_{i,t}^{min} \) and \( DT_{i,t}^{max} \) are the minimum and maximum departure time of the last train in line \( l_i^g \).

3) OBJECTIVE FUNCTION

The objective of the last train transfers optimization is to maximize the passenger flow who can successfully transfer in the whole network during the last train period.

\[
\max Z = \sum_{i,g} \sum_{j,h} \sum_{m} \delta_{i,t,j}^{uw} Q_{i,t,j}^{sw} 
\]

where \( Q_{i,t,j}^{sw} \) is the passenger flow at station \( S_m \) from line \( l_i^g \) to line \( l_j^h \) in the whole network.

4) SOLUTION ALGORITHM

Developing a coordination train schedule for last trains is quite complicated because it contains many independent variables and involves a variety of constraints. Ibarra-Rojas[32] has shown that the timetable synchronization problem of bus and metro belongs to the NP-hard problem set because of the large number of variables and constraints. To obtain an optimization train schedule within an acceptable time, heuristic algorithms such as Simulated Annealing (SA), Tabu Searching (TS), Neural Network...
(NN) and Genetic Algorithm (GA), are commonly used to solve the problems. Among those algorithms, GA is the most suitable to the current issue: since, (1) the last train coordination model variables are discrete so they lend themselves to encoding as chromosomes, and it is relatively easy to generate chromosomes using model variables; (2) the model variables would not exceed the constraints limitation of last train departure period for each iteration of crossover and mutation operations.

Thus, we apply GA as the solution algorithm to solve the proposed model. Here, the departure time of last trains from the original station which are the decision variables of the proposed method is selected as the chromosome, while the objective function is selected as the fitness value. The station dwelling time and the section running time are regarded as fixed parameters, then the last train coordination can be achieved by the adjustment of the departure time of last trains from the original station in different metro lines.

IV. CASE STUDY

The proposed method is validated based on the Shenzhen metro network, which operates 8 transit lines connecting 199 stations and transports about 3.2 million passengers a day of March 2018, shown in Figure 11. In this case, the transfer station of “Baoan Center”, red circle in the figure, is selected as an example to show the process of potential demand for last trains and the coordination of last train transfers. Metro line 1 (green line) and line 5 (purple line) are involved metro lines in studying the potential passenger demand for last trains.

We select a typical Friday (3/16/2018) with good weather and no sport or concert events as an example to deal with the case study. Usually, there is more night passenger demand on Friday compared with other weekdays. Because more people prefer to work late or stay late for entertainment at Friday night since Saturday day is not working day. Hence, there is a more desperate need to study Friday late night metro demand.

FIGURE 11 The topological network of Shenzhen metro network

A. ANALYSIS OF POTENTIAL PASSENGER DEMAND

All data needed in the case study are listed below. All data source are collected from the Shenzhen public transport systems.

a) **Metro passenger flow**: there are total 3,203,762 passengers over the whole day who travel through the metro system.

b) **Taxi passenger flow**: total 864,305 records are generating over the whole day, among which 42,207 records generated during the last train period.

c) **Bus passenger flow**: total 1,036,732 records are generating over the whole day, among which 8,324 smart records generate during last train period.

d) **GPS data**: the GPS data of taxi and bus, and also the geography information of metro stations and bus stations are acquired.

1) A solution for bus

We first use the proposed solution for the bus data to deal with the bus GPS data. It is known that the bus GPS data and smart card data are few during midnight compared with the regular period. The left of Figure 12 shows the bus passenger flow whose origin is close to the target station. According to Algorithm 1, the potential passenger demand is calculated according to the principle that the destination stations of bus trips should belong to the target metro lines, as shown in the right of Figure 12. The same trips are gathered together, and most passengers move to the rest stations of metro Line 1.

It should be noted that more historical bus data are needed to speculate the possible alighting location for passengers.
2) A solution for taxi

In the same way, we apply the solution for the taxi data to the case study. After filtering the GPS data to remain the taxi traffic data whose origin is close to the target station (Baoan Center), the taxi passenger flow during last train period could be obtained, as shown in the left of Figure 13. Based on the filtered result, the taxi passenger flow is assigned to the metro lines which is related to the target station according to Algorithm 2, as shown in the right of Figure 13. Consequently, the potential passenger flow using taxi data is calculated. Compared with bus data, taxi data indicate more passenger demands to more destination stations.

3) Combination of two results

After calculating the potential demand using both taxi and bus data, all these potential flows are combined to form an integrated potential passenger demand for last trains. The combining result is shown in Figure 14. Moreover, the passenger demand data are the sum of passenger flow in different directions, which are displayed in Table VII. In this table, the directions of upstream (↑) and downstream (↓) mean the train operation directions of metro lines. Each line has two operation directions. The numbers of (01) and (05) in the table represent metro Line 1 (green line) and Line 5 (purple line). This table shows that the direction containing the biggest flow is transit Line 1 downstream in the table.
As stated above, the passenger flow of last trains contains not only the passengers’ transfer to taxi or bus due to failing to board the last trains but also the passengers who succeed to board the last trains. The flow of passengers who succeed to board the last trains is displayed in Table VIII, which is obtained from the AFC system. Therefore, the total potential passenger flow of last trains is summed up by combining all traffic data source. The result is shown in Table IX. The values of potential passenger demand reveal the importance of transfer directions at the target station, which is quite useful to make an optimized last train schedule.

| TABLE VII
| THE POTENTIAL PASSENGER FLOW FOR LAST TRAINS FROM TAXI AND BUS DATA |
|---|---|---|---|---|---|
|   | 01↑ | 01↓ | 05↑ | 05↓ | SUM |
| Taxi | 47  | 213 | 37  | 0   | 297 |
| Bus  | 16  | 143 | 4   | 0   | 163 |
| SUM | 63  | 356 | 41  | 0   | 460 |

*↑: Upstream; ↓: Downstream

The first part accounts for the potential passenger demand for last trains using the proposed data-driven method. It is found that the more days’ traffic data in the same typical day used in the proposed method, including metro AFC data, taxi data, and bus data, the more accuracy and correctness of the potential passenger demand the proposed method can be produced.

B. Coordination of last train transfers

In this section, a part of the Shenzhen metro network is selected to realize the coordination method. There are 4 metro lines and 5 transfer stations. The topological diagram of the metro network is shown in Figure 15. The black circle in the figure represents the transfer station, and the letters represent the code of the transfer station. Here, Station B is Baoan Center, which is the target station studied in Section 4.1. Different color lines represent different metro lines. Considering that the metro line is divided into upstream and downstream directions, the black arrow refers to the upstream direction of the metro line.

| TABLE VIII
<p>| THE PASSENGER FLOW FOR LAST TRAINS OBTAINED BY THE AFC SYSTEM |</p>
<table>
<thead>
<tr>
<th>Baohan Center</th>
<th>01↑</th>
<th>01↓</th>
<th>05↑</th>
<th>05↓</th>
</tr>
</thead>
<tbody>
<tr>
<td>01↑</td>
<td>\</td>
<td>0</td>
<td>712</td>
<td>60</td>
</tr>
<tr>
<td>01↓</td>
<td>0</td>
<td>\</td>
<td>79</td>
<td>11</td>
</tr>
<tr>
<td>05↑</td>
<td>14</td>
<td>77</td>
<td>\</td>
<td>0</td>
</tr>
<tr>
<td>05↓</td>
<td>569</td>
<td>626</td>
<td>0</td>
<td>\</td>
</tr>
</tbody>
</table>

| TABLE IX
<p>| THE POTENTIAL PASSENGER FLOW FOR ALL TRANSFER DIRECTIONS OF LAST TRAINS |</p>
<table>
<thead>
<tr>
<th>Baohan Center</th>
<th>01↑</th>
<th>01↓</th>
<th>05↑</th>
<th>05↓</th>
</tr>
</thead>
<tbody>
<tr>
<td>01↑</td>
<td>\</td>
<td>0</td>
<td>753</td>
<td>60</td>
</tr>
<tr>
<td>01↓</td>
<td>0</td>
<td>\</td>
<td>79</td>
<td>11</td>
</tr>
</tbody>
</table>

FIGURE 14  The potential passenger flow combining taxi and bus data
Table X shows the example of transfer direction ordered by passenger demand during the last train period. The passenger demand of station B(Baoan station) is acquired from section 4.1. Table XI shows the original departure time and optimized departure time interval for the last trains.

### Table X

**Example of Transfer Direction Ordered by Passenger Demand During the Last Train Period**

<table>
<thead>
<tr>
<th>Transfer Stations</th>
<th>Transfer out Direction</th>
<th>Transfer in Direction</th>
<th>Transfer walking time /min</th>
<th>Passenger flow/person</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>01↓</td>
<td>02↓</td>
<td>1</td>
<td>1132</td>
<td>1</td>
</tr>
<tr>
<td>B(Baoan Center)</td>
<td>05↓</td>
<td>01↓</td>
<td>1.5</td>
<td>982</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>01↑</td>
<td>02↑</td>
<td>1</td>
<td>918</td>
<td>3</td>
</tr>
<tr>
<td>B(Baoan Center)</td>
<td>01↑</td>
<td>05↑</td>
<td>4.4</td>
<td>753</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>02↓</td>
<td>01↓</td>
<td>1.2</td>
<td>726</td>
<td>5</td>
</tr>
<tr>
<td>B(Baoan Center)</td>
<td>01↓</td>
<td>05↑</td>
<td>1.4</td>
<td>709</td>
<td>6</td>
</tr>
<tr>
<td>B(Baoan Center)</td>
<td>05↓</td>
<td>01↑</td>
<td>1.5</td>
<td>632</td>
<td>7</td>
</tr>
<tr>
<td>E</td>
<td>02↑</td>
<td>01↑</td>
<td>1.2</td>
<td>608</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>05↑</td>
<td>07↓</td>
<td>2</td>
<td>378</td>
<td>9</td>
</tr>
<tr>
<td>C</td>
<td>05↓</td>
<td>07↑</td>
<td>2</td>
<td>336</td>
<td>10</td>
</tr>
</tbody>
</table>

---

*↑: Upstream; ↓: Downstream

### Table XI

**Original Departure Time and Optimized Departure Time Interval for Last Trains**

<table>
<thead>
<tr>
<th>Transit Line</th>
<th>Initial departure time</th>
<th>Optimized departure time interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>05↑</td>
<td>23:00:00</td>
<td>[22:45,23:15]</td>
</tr>
<tr>
<td>05↓</td>
<td>23:03:00</td>
<td>[22:48,23:18]</td>
</tr>
<tr>
<td>01↑</td>
<td>23:00:00</td>
<td>[22:45,23:15]</td>
</tr>
<tr>
<td>01↓</td>
<td>23:00:00</td>
<td>[22:45,23:15]</td>
</tr>
<tr>
<td>07↑</td>
<td>23:00:00</td>
<td>[22:45,23:15]</td>
</tr>
<tr>
<td>07↓</td>
<td>23:00:00</td>
<td>[22:45,23:15]</td>
</tr>
<tr>
<td>02↑</td>
<td>23:00:00</td>
<td>[22:45,23:15]</td>
</tr>
<tr>
<td>02↓</td>
<td>23:00:00</td>
<td>[22:53,23:23]</td>
</tr>
</tbody>
</table>

In order to optimize the coordination of last train transfers, the parameters of the genetic algorithm need to be set in advance. After several experiments and comparisons, the parameters are set as follows could obtain a relative result: the population size is set to 50, the crossover probability is set to 0.95, the mutation probability is set to 0.05, and the termination algebra is set to 2000.

In the original scheme used in the case study, there are 15 connecting transfer directions among total 24 directions, and 3041 persons connecting in these transfer directions. Considering the characteristic of metro operation period and the need for last train demand, the last train schedule is optimized after applying the proposed method and the solving algorithm. The optimized result of last train transfers is shown in Table XII. Compared with the original scheme, the proposed scheme can achieve 18 of the 24 connecting transfer directions and carry about 3,989 persons, as shown in Figure 16. Therefore, under the given constraints, the proposed optimization coordination of last train transfers could achieve the maximum transfer of passenger demand, and it could ensure more passengers boarding the last trains after transfer in metro systems.
This paper focuses on the coordination of last train transfers using potential passenger demand from public transport modes including taxi and bus. Firstly, the proposed method takes full use of passenger flow data collected by the AFC system and public transport data. A solving solution for taxi and bus is carried out to calculate the potential passenger demand in the transfer direction of the target station. Then, a model is built based on the purpose of maximizing the passengers who can board their last trains successfully, and the genetic algorithm is applied to solve the model. Finally, the proposed method has been successfully tested in the case study with real-world data, Shenzhen metro. In the case, the result of the potential passenger demand is applied as an input condition to the optimization coordination of last train transfers. Our future study will consider more traffic modes except for taxi and bus, and improve the accuracy and correctness of the proposed data-driven method. Further study will also focus on extending the study of late night demand under different conditions.

REFERENCES


