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Optimization for Feeder Bus Route Model Design with Station Transfer

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Abstract: To fully take the advantages of conventional bus and subway, and to maximize the overall feeder efficiency of the public transport system, the topic of feeder bus route optimization is studied in this paper. Considering the origin destination demand of passenger flow between subway stations and bus stations and transfer characteristics, the objective function is established with the minimum sum of bus operation cost and passenger travel cost. Taking into account the integrity of the feeder bus route, the rationality of the route, the route capacity and the station transfer factors, the constraints of the optimization model are constructed. Based on the idea of the genetic algorithm, the solution algorithm of the optimization model is developed. The genetic algorithm and enumeration algorithm are used to solve the optimization of the feeder bus route in this case, and the accuracy and efficiency of the solution are analyzed. The influence of the number of feeder bus routes on the system in the case network is compared and discussed. We compare and analyze the differences between the original bus network and the feeder bus network in terms of bus operation cost, passenger flow demand and total passenger travel cost. The research shows that the model and algorithm can find the approximate optimal solution of the feeder bus network scheme related to the subway through fewer iterations. The number of routes in the model has little impact on the whole feeder system, and the optimization scheme using five routes is effective and reasonable in this paper. Compared with the existing bus network, the optimization scheme has obvious advantages in improving the passenger-carrying rate, reducing the per capita travel cost and improving the overall operation efficiency of the system.

Keywords: traffic engineering; route optimization; genetic algorithm; feeder bus; station transfer

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1. Introduction

1.1. Background

With the rapid development of the urban social economy and the increasing travel demand of residents, the problem of urban traffic congestion is becoming more and more prominent. For a long time, the subway has been recognized as an effective means to alleviate urban traffic congestion because of its advantages such as large capacity, long haul distances and fast speed. However, compared with the subway, although the conventional bus has a small capacity and slow speed, it has the advantages of low cost, strong accessibility and wide coverage. It can still maintain a long-term competitive and cooperative relationship with the subway. Therefore, studying the optimization of subway connecting bus lines can build a perfect connecting bus service system, give full play to their advantages, expand cooperation and reduce competition. It can also create convenient conditions for residents to travel and attract more residents to choose buses or subways. It is of great significance to optimize the structure of residents' travel mode and alleviate traffic congestion.

1.2. Literature Review

At home and abroad, most of the research on the feeder bus focused on the feeder mode in the early stage. Literature [1,2] discussed the M-1 feeder mode, which designed an optimized feeder route to send passengers from different origins to the same destination. In most bus services, the departure and destination of passengers were different. Therefore, Koon et al. [3] and Chien et al. [4] considered the M-M mode to find the optimal feeder bus line network to meet the needs of passengers from different origins to different destinations. In recent years, the optimization model and algorithm of the feeder bus route were studied. Among them, the leading idea was the genetic algorithm. To solve the problem of a better connection between bus and subway, Wei et al. [5] constructed a feeder bus route optimization model, which was solved by a genetic algorithm, and verified its feasibility through case analysis. Taplin et al. [6] and Li et al. [7] considered the feeder bus route and passenger walking distance and used a genetic algorithm to solve the optimization model of the feeder bus route. Vanany et al. [8] proposed a genetic-algorithm-based approach to develop a feeder bus routing model to determine the best flow of routes and the minimum number of feeder buses. Besides the widely used genetic algorithms, some other algorithms are also in use to develop a feeder bus routing model. Lin et al. [9] constructed a multi-objective optimization model with the shortest feeder route, the shortest passenger travel time and the largest feeder service range as the objective function. The satisfactory route was obtained by fuzzy programming and the TOPSIS method. Dou et al. [10] proposed a solution to the feeder bus timetabling problem. An MINLP model was developed to minimize the weighted sum of passenger cost and bus operating cost. A hybrid artificial bee colony (ABC) algorithm was developed to solve it. Badia et al. [11] discussed the service schemes of fixed routes and door-to-door services using the numerical analysis method. The results show that the fixed-route service was more effective. Sun et al. [12] established a mixed-integer linear programming model aiming at minimizing the total travel time of all passengers. A distributed genetic algorithm was designed, and its effectiveness was verified. In addition, a few scholars have considered other factors in the feeder route optimization problem. For example, Guo et al. [13] analyzed factors such as land type and travel demand and built a model with the optimization goal of maximizing transportation efficiency. Zhang et al. [14] considered the impact of environmental factors and constructed an optimization model based on the cost constraint of carbon emissions. Park et al. [15] proposed a design method of the feeder bus route based on the taxi movement mode.

Although researchers have conducted some studies on feeder bus route optimization, they mainly focused on the optimization algorithm itself. Most of the existing studies focus on the objectives of maximizing feeder efficiency and minimizing the departure interval [16,17] and rarely balance the interests of both bus operators and passengers. In addition, there is a lack of consideration of station transfer factors in the feeder bus route optimization model. In view of the above gaps, this paper contributes to the existing literature on the feeder bus route related to the subway in three ways:

1. Considering that the passenger flow transfer scheme between different OD demand points also changes when the feeder bus network scheme changes, resulting in the change of passenger travel time and cost, a multi-objective optimization model of the feeder bus route is constructed. This fills the gap that the station transfer factor is not considered in the previous literature.
2. In the optimization model, the increase of ride cost caused by transfer times and transfer time are considered to punish the transfer cost, taking into account the interests of both bus operators and passengers, and filling the gap of the existing feeder bus route optimization model.
3. In the case analysis, the number of feeder bus routes is taken as a factor affecting the feeder system, and the sensitivity analysis is carried out to verify the feasibility of the optimization results.

The research results have important theoretical reference significance for the development and improvement of the system planning theory of the feeder bus related to the subway and have important practical application value for improving residents' travel convenience, enhancing the operation efficiency and attraction of the public transport system and optimizing residents' travel mode structure.

The remainder of this paper is organized as follows. Section 2 gives the problem description and model assumptions of the optimization model of the feeder bus route related to the subway. Section 3 is the construction of the optimization model, using the characteristics of the station transfer and the penalty function to limit, to ensure the fairness of the interests of both parties, and the enthusiasm of the feeder bus mode of travel. In Section 4, we design a genetic algorithm to solve the optimization model. Then, a case study is conducted to verify the optimization effect and application feasibility of the feeder bus route optimization model based on a genetic algorithm in Section 5. Finally, Sections 6 and 7 present the discussions and conclusions of this paper.

2. Problem Description and Model Assumptions

2.1. Problem Description

The feeder bus related to the subway is a feeder mode in which passengers from each station are transported to the subway station by means of bus lines, and passengers leaving the subway station are evacuated to their respective destinations. The optimization of this kind of bus route is based on the vehicle routing problem, considering the problems of subway feeder stations, bus stations, passenger flow demand and station transfer, and on the premise of meeting the needs of passengers arriving at the subway station, the optimization selection and design of the feeder route are carried out. The following mathematical description can be made:

There are m subway stations $(1, 2, \ldots, m)$ and n bus stations $(1, 2, \ldots, n)$ in the road network. There are also s routes available for feeder services $(1, 2, \ldots, s)$. The maximum passenger flow capacity of each line is *Qmax*, the capacity of each transfer station is B, and the line operation frequency is f. In the road network, the passenger flow demand served by the s bus line between each two stations is ${q_{ij}}^s$, and the number of connecting bus lines at each transfer station is *Route*. Under the conditions of ${q_{ij}}^s \leq Q_{max}$ and $Route \leq B/f$, the optimal feeder route scheme is required to minimize the sum of bus operation cost and passenger travel cost. The schematic diagram of the feeder bus route model is shown in Figure 1.

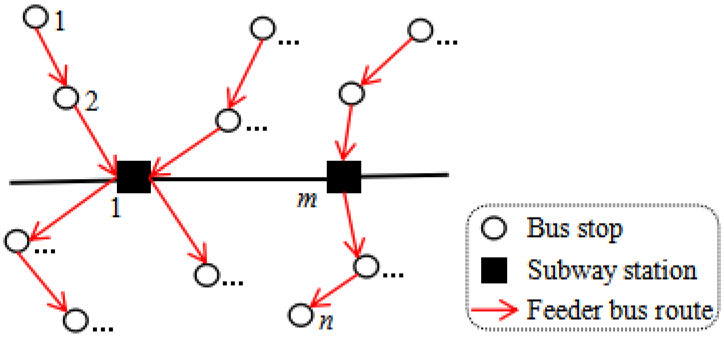


Figure 1. Diagram of feeder bus route model.

2.2. Assumptions

For the convenience of modeling and solving, the following model assumptions are made in this study: Each bus stop is served by only one feeder bus route. Each feeder bus route serves only one subway station. The feeder bus stops at every bus stop on its route without crossing stations. The speed of feeder buses and subways is known. The departure interval of the feeder buses and the subway remains unchanged, and its number is constant. The departure interval is assumed to be 6 min and 7 min.

2.3. Parameter Definition

The notations used throughout this paper are listed in Table 1.

Table 1. Parameters and variables in the optimization model.

Symbol	Definition
Collections and indexes	
V	Set of all nodes
B	Collection of bus stops
T	Collection of subway stations
O, D	Collection of starting stations, ending stations $O, D \subset B$
S	Collection of bus routes
i, j, m, n, a	Index of all nodes (bus stops and subway stations)
s	Index of feeder bus routes
Related parameters	
c_0	Operating cost per unit distance of feeder buses
c_1	Travel cost per passenger unit time
d_{ij}	Actual distance from station i to j
T_{ij}	Travel time from station i to j
t^a, t^b	Transfer time at stations a, b
t_{walk}	Walking time required for bus transfer to subway
v_{mn}	Travel speed from station m to n
q_{ij}	Passenger flow from i to j
N_{max}	Maximum number of stations
Q	Single node capacity
Q_{max}	Maximum passenger flow capacity of each shuttle bus on the route
f_{bus}, f_{subway}	Operation frequency of feeder bus and subway
B	Capacity of transfer station
$B^{'}$	Capacity of a single berth
N	Actual parking number at transfer station
g/c	Intersection split
t_c	The time from closing the bus to remerging into the traffic flow after leaving the station
t_d	Average stop time
α	Expected failure rate, that is, the probability of waiting outside the bus stop
Z_α	Expected failure rate α corresponding to standard normal distribution value, namely the bus non-uniform arrival coefficient
c_v	Unbalanced coefficient of vehicle parking time
r	Excessive transfer penalty coefficient
$Route$	Number of routes passed by each subway station
P_{ij}	Penalty function for too many transfers from i to j
n_{ij}	Transfer times from point i to point j
Decision variables	
x_{mn}^s	$x_{mn}^s = 1$ if $m,\ n$ is on line s; x_{mn}^s = 0, otherwise
y_{mn}^{ij}	$y_{mn}^{ij} = 1$ if the road section of m and n is on the route of i and j; y_{mn}^{ij} = 0, otherwise
y_{ij}	$y_{ij} = 1$ if passengers depart from i to j; y_{ij}=0, otherwise
z_{ij}^a	$z_{ij}^a = 1$ if there is transfer from I to j at station a; z_{ij}^a = 0, otherwise
y_i^s	$z_{ij}^a = 1$ if station I is on line s; z_{ij}^a = 0, otherwise

3. Model Development

3.1. Feeder Bus Route Integrity Constraints

The integrity constraint of the feeder route represents the basic rules of the feeder bus running on the road network, as shown in Equations (1) and (2).

$$\sum_{i \in B} \sum_{j \in T} x_{ij}^s = 1, \forall s \in S \tag{1}$$

$$\sum_{s \in S} y_i^s = 1, \forall i \in B \tag{2}$$

Equation (1) ensures that each feeder bus route serves only one subway station. Equation (2) ensures that each bus stop has only one feeder bus route connected to it.

3.2. Route Rationality Constraints

If the number of stations on the feeder route is too large, the detour distance and travel time will be increased; if the number of stations on the feeder route is too small, the passenger volume of the route will be affected. Therefore, the number of stations on each feeder route shall meet Equation (3):

$$\sum_{i \in V} y_i^s \le N_{\max}, \ \forall s \in S \tag{3}$$

Any feeder route must ensure that there is no loop, that is, it meets Equation (4):

$$0 \le \sum_{i \in V - \{O,D\}} x_{ik}^s + \sum_{i \in V - \{O,D\}} x_{ki}^s \le 1, \forall k \in V - \{O, D\} \tag{4}$$

The following constraints should be met for the starting, ending and intermediate nodes on any feeder route:

$$\sum_{i \in V(i \ne k)} x_{ik}^s = 0, \sum_{j \in V(k \ne j)} x_{kj}^s = 1, \forall k \in O \tag{5}$$

$$\sum_{i \in V(i \ne k)} x_{ik}^s = 1, \sum_{j \in V(k \ne j)} x_{kj}^s = 0, \forall k \in D \tag{6}$$

$$\sum_{i \in V(i \ne k)} x_{ik}^s = \sum_{j \in V(k \ne j)} x_{kj}^s = 1, \forall k \in V - \{O, D\} \tag{7}$$

For the starting point, Equation (5) ensures that there is no path to the starting point, and there is only one path sent by the starting point. For the ending point, Equation (6) ensures that the ending point can only be in not out. For intermediate stations, Equation (7) ensures that if route s passes through node k, there is only one path for j to enter station k and exit station k.

3.3. Route Capacity Constraints

Equations (8) and (9) are the constraints on the transport capacity of the feeder bus route. While ensuring that the transport capacity of any feeder bus route does not exceed the maximum passenger flow transport capacity of the route, it also ensures that the capacity of the feeder bus to each node does not exceed the limit.

$$\sum_{i \in V} q_{ij} \times x_{ij}^s + q_{ij} \times \left(1 - x_{ij}^s\right) \times z_{ij}^a \le Q \ \ \forall j \in V, \forall a \in T, \forall s \in S \tag{8}$$

$$\sum_{i \in V} \sum_{j \in V} q_{ij} \times x_{ij}^s \le Q_{\max} \ \ \forall s \in S \tag{9}$$

3.4. Station Transfer Constraints

When passengers travel, transfer behavior is inevitable. Transfer behavior exists between buses and buses and between buses and subways. In the process of solving the model, different route schemes should be searched and screened. At this time, the passenger transfer behavior between two points will change with different route schemes, which will affect the passenger travel cost between the two points, which is the key consideration of this study different from previous studies.

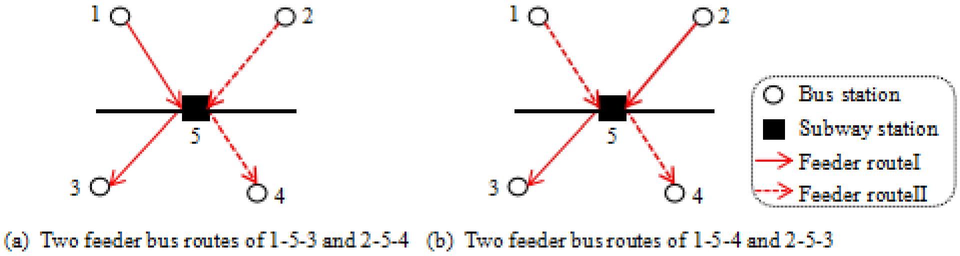
As shown in Figure 2, if the passenger is going to travel from point 1 to point 3, the feeder scheme of Figure 2a is obtained during the first route search. At this time, the passenger at point 1 can directly reach destination 3 through route I, and the travel cost of this section is $c_1 \times q_{13} \times \frac{d_{13}}{v_{bus}}$. However, when the route is searched again, the feeder scheme changes, such as Figure 2b; at this time, the passengers at point 1 need to transfer at the subway station and take the feeder bus to point 3, and the travel cost of this section is $c_1 \times q_{13} \times \left(\frac{d_{13}}{v_{bus}} + t^5 + P_{13}\right)$.

$$\begin{matrix} y^{ij}_{ma} = y^{ij}_{an} = 1, \forall m \in B \vee T, \forall a \in T, \forall n \in T \vee B \\ x^s_{ij} = 0, \forall i,j \in B \cup T, \forall s \in S \end{matrix} \Rightarrow \sum_{s \in S} y^s_i \leq Route \forall i \in T \quad (10)$$

$$\begin{matrix} y^{ij}_{mb} = y^{ij}_{bn} = 1, \forall m,n \in B, \forall b \in T \\ x^s_{ij} = 0, \forall i,j \in B \cup T, \forall s \in S \end{matrix} \Rightarrow \sum_{s \in S} y^s_i \geq 2 \forall i \in T \quad (11)$$

$$t^a = t_{walk} + \frac{1}{2f_{subway}} \quad (12)$$

$$t^b = \frac{1}{2f_{bus}} \quad (13)$$



(a) Two feeder bus routes of 1-5-3 and 2-5-4 (b) Two feeder bus routes of 1-5-4 and 2-5-3

Figure 2. Diagram of station transfer.

Equations (10) and (11) respectively define a as the transfer station between the bus and the subway on the route from i to j; b is the transfer station between bus and bus on the route from i to j. Equations (12) and (13) respectively define the transfer time of bus–subway and bus–bus.

$$B = NB' \quad (14)$$

$$B' = \frac{3600(g/c)}{t_c + t_d(g/c) + t_{om}} = \frac{3600(g/c)}{t_c + t_d(g/c) + Z_a c_v t_d} \quad (15)$$

$$Route \leq \frac{B_i}{f_i} \quad (16)$$

Equations (14) and (15) calculate the capacity of transfer stations. Equation (16) represents the bus route capacity served by the transfer station.

3.5. Cost Analysis

The layout of the feeder bus route needs to take into account the interests of both passengers and bus operators so as to ensure the enthusiasm of travelers in using public transport and the economic benefits of bus operators. Therefore, the minimum total cost of the feeder bus route system is the basis for the design of the route.

In terms of bus operation, the operation cost of feeder bus vehicles is mainly considered. The operating costs of bus vehicles include fuel costs, labor costs, depreciation costs, etc., which are positively related to the operating mileage of each feeder route. The number of buses will affect the transportation distance, which will determine its operating cost. Equation (17) represents operating costs.

$$Z_1 = c_0 \sum_{i \in V} \sum_{j \in V} d_{ij} \times x^s_{ij} \quad (17)$$

In terms of passengers, the generalized travel cost of passengers in the whole travel is mainly considered, including the travel time cost and transfer time cost of all passengers. The travel time of passengers includes the time of direct travel without transfer, as shown in Equation (18). The time of travel and transfer is shown in Equation (19). The total travel time of passengers is shown in Equation (20).

$$T_{ij}^{1} = \sum_{m \in B \cup T} \sum_{n \in B \cup T} \frac{d_{mn}}{v_{bus}} \times y_{mn}^{ij} \times x_{ij}^{s} \tag{18}$$

$$T_{ij}^{2} = \sum_{m \in B \cup T} \sum_{n \in B \cup T} \frac{d_{mn}}{v_{mn}} \times y_{mn}^{ij} \times \left(1 - x_{ij}^{s}\right) + \sum_{a \in T} t^{a} \times z_{ij}^{a} + \sum_{b \in T} t^{b} \times z_{ij}^{b} \tag{19}$$

$$T_{ij} = {T^{1}}_{ij} + {T_{ij}}^{2} \tag{20}$$

In addition, in public transport travel, compared with direct and one-time transfers, multiple transfers usually make travelers tired. Considering passenger comfort, the penalty function is used to increase the cost of multiple transfers so as to punish the behavior of changing two or more times. The penalty function is shown in Equation (21), and the total travel cost of passengers is shown in Equation (22).

$$P_{ij} = \begin{cases} 0 & n_{ij} \leq 1 \\ r \times t^{a} \times n_{ij} & n_{ij} > 1 \end{cases} \tag{21}$$

$$Z_2 = c_1 \sum_{i \in B \cup T} \sum_{j \in B \cup T} q_{ij} \times \left(T_{ij} + P_{ij}\right) \times y_{ij} \tag{22}$$

3.6. Objective Function

Based on the cost analysis of the feeder bus system, the optimization model is established with the optimization goal of minimizing the sum of bus operation cost and passenger travel cost, as shown in Equation (23).

$$\min Z = c_0 \sum_{i \in B \cup T} \sum_{j \in B \cup T} d_{ij} \times x_{ij}^{s} + c_1 \sum_{i \in B \cup T} \sum_{j \in B \cup T} q_{ij} \times \left(T_{ij} + P_{ij}\right) \times y_{ij} \tag{23}$$

According to Sections 2 and 3, the methods directly relevant to this paper that address the feeder bus route optimization problem are listed in Table 2.

Table 2. Related methods for feeder bus with consideration of route optimization.

Categories	**Constraints**			
	Route Integrity	**Route Rationality**	**Route Capacity**	**Station Transfer**
Existing studies	Fixed	Fixed	Conservation of bus capacity and number of passengers	Considered transfer behavior and introduced transfer time
This paper	Fixed	Fixed	Simultaneous restriction of route capacity and capacity of each node	Clarified the characteristics of station transfer and introduced multiple-transfer penalty

4. Genetic Algorithm

In this section, we use a genetic algorithm to solve the optimization model of the feeder bus route, and the reasons are as follows. Genetic algorithm starts from the string set of problem solutions, which has large coverage and is conducive to global optimization; genetic algorithm uses the transition rules of probability to guide its search direction and has the habit of self-organization, self-adaptation and self-study; genetic algorithm itself is easy to implement and optimize.

4.1. Chromosome Coding

In this paper, the chromosome is coded by a natural number, and the research object includes m subway stations, s feeder routes and n bus stops. The chromosome code is divided into three segments. The first segment is the number of subway stations passed by each route, the second segment is the number of bus stops passed by each route, and the third segment is the number of bus stops passed in order. Therefore, the chromosome coding length is $2 \times s + n$, whose solution vector is expressed as $(rail_1, rail_2, \ldots, rail_s; Num_1, Num_2, \ldots, Num_s; i_1, i_2, \ldots, i_n)$.

4.2. Fitness Evaluation

The fitness of a genetic algorithm is used to measure the advantages and disadvantages of individuals in the optimization process. In this paper, the fitness evaluation function is constructed by using the objective function, and the excellent individuals are selected by roulette. The higher the fitness value of individuals, the larger the sector area in roulette, and the greater the probability of being selected.

4.3. Crossover and Mutation Operation

Multi-point crossover is adopted to implement the operation with a crossover probability of 0.6. Therefore, the following crossover operators are designed in this paper:

For parental chromosomes, three positions are randomly selected from the first, second and third segments of the two parental chromosomes for gene exchange to produce two offspring chromosomes.

For offspring chromosomes, verification and correction of the coding are required. For the second section, if the total number of bus stops after crossing is inconsistent with the actual total number of stops, then increase or decrease. For the third section, if duplicate stations are generated after crossing, the duplicate stations will be deleted, and the stations that do not appear will be filled in.

The mutation method adopts a simple mutation. In order to enhance the global search ability, the mutation operation is carried out with the probability of 0.1. Three mutation positions were selected from the three segments of chromosomes, and the three mutation positions were randomly exchanged to obtain a new chromosome. At this time, the passing order of the stations has changed after the interchange for the feeder route problem; that is, the solution of the feeder route problem has been updated. The specific solution flow chart of the genetic algorithm is shown in Figure 3.

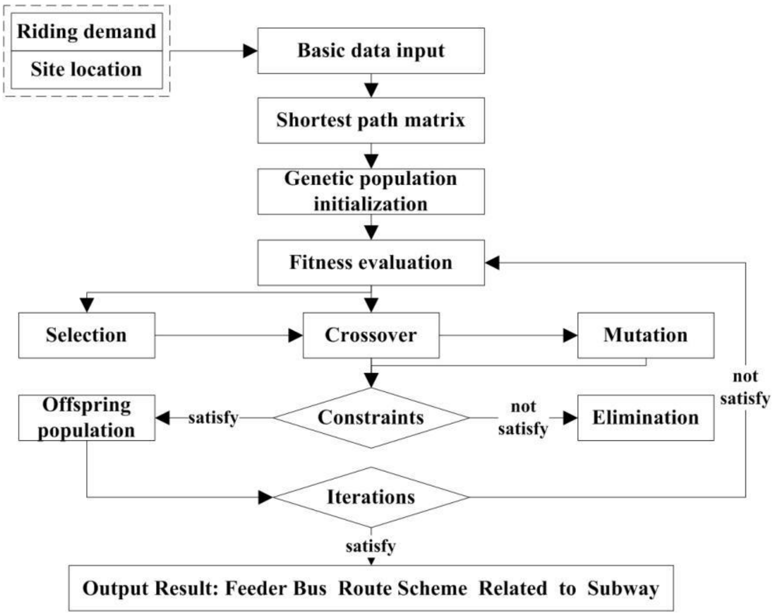


Figure 3. Flow chart of genetic algorithm.

5. Case Study

5.1. Case General Situation

Because the whole subway line is long and there are many bus stops along the line, in order to facilitate the calculation and explain the idea of the model, three subway stations of Dalian Metro Line 1 and 27 bus stops along the line are selected as a case study. Through the survey, the location of each station in this area is obtained, as shown in Figure 4. Among them, the number 1–3 is the subway station number, 4–30 is the bus station numbers.

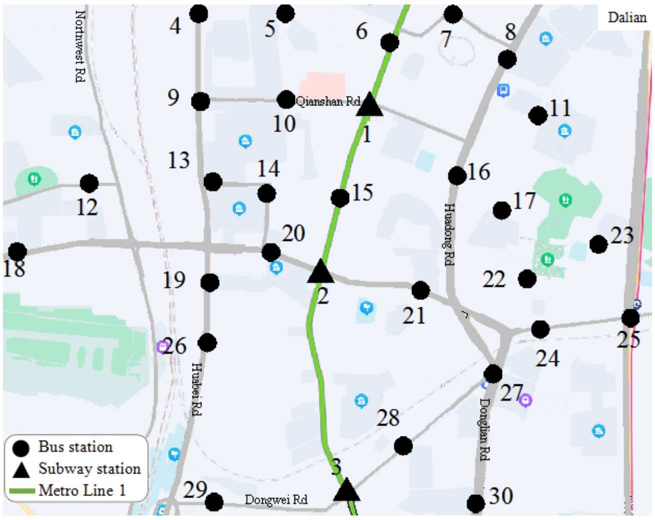


Figure 4. Distribution of stations.

The OD data of passenger flow are obtained by sampling a questionnaire survey. One investigator is arranged at each bus stop to conduct a random sampling questionnaire survey on waiting passengers. The survey time is 2 h at the peak, the survey content is the starting and ending points of travelers, and the total number of waiting passengers in 2 h is recorded to obtain the sampling rate. We sort out all questionnaires, summarize the questionnaires with passenger demands in this case area and obtain sample OD data. Then the sample expansion is carried out according to the survey sampling rate to obtain the overall passenger flow OD data. The investigated passengers are randomly selected, and thus their OD is randomly distributed.

Based on the passenger flow obtained from the survey, this paper formulates the departure interval, which is based on the passenger flow at peak hours, so as to determine the number of buses. If the pick-up bus can be implemented during peak hours, the determined number of buses will meet the transportation of all passenger flows within that day.

According to the existing operation standards of bus and subway in Dalian, the operation speed of a bus is 25 km/h, the operation speed of the subway is 80 km/h, and the cost coefficient c_0 within the unit distance of receiving public transport is 25 CNY/km. According to the salary level report of Dalian in 2018, the travel cost coefficient c_1 per unit time of passengers is 26 CNY/h.

5.2. Model Solving

The genetic algorithm is programmed with MATLAB. The initial population size is 60. After 300 generations of evolution, the fitness function tends to be stable, and the final result is obtained. After three runs, the fitness function is obtained, as shown in Figure 5.

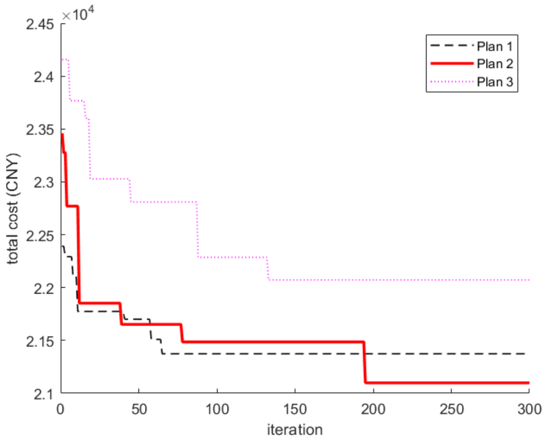


Figure 5. Relation curve between iteration times and objective function.

According to Figure 5, the objective function tends to be stable after 200 iterations, and the total cost of the optimal system is CNY 21,099.3. The feeder route is shown in Figure 6. Colored lines represent different branch routes. The number 1–3 is the subway station number, 4–30 is the bus station numbers.

In order to verify the solution accuracy, the total cost of obtaining the global optimal solution of the system by MATLAB programming enumeration method is CNY 20,386.1. The optimization results of feeder routes obtained by the genetic algorithm and enumeration method are shown in Table 3. The comparison of the operational performance of the two algorithms is shown in Table 4.

According to the data comparison in Table 4, although the enumeration method can obtain the global optimal solution, the operation time of the genetic algorithm is much less than that of the enumeration method under the same calculation scale. It can be predicted that with the expansion of road network scale and demand to the city level, the computational timeliness of the enumeration method becomes significantly worse and cannot meet the needs of a large-scale solution. In terms of calculation accuracy, the results of multiple runs of the genetic algorithm have little fluctuation, and the minimum error between the genetic algorithm and global optimal solution is only 3.5%, which is within a reasonable range.

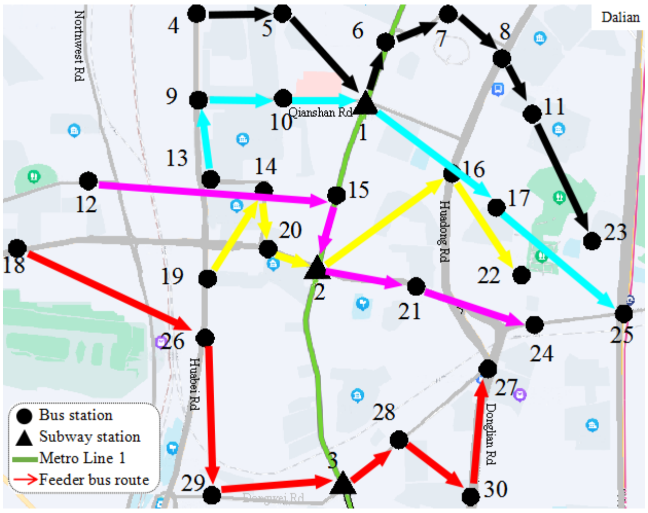


Figure 6. Optimization results of feeder bus route.

Table 3. Optimization results of feeder bus route.

Route	Genetic Algorithm		Enumeration Method	
	Route Optimization	Total System Cost (CNY)	Route Optimization	Total System Cost (CNY)
1	4-5-1-6-7-8-11-23	21,099.3	4-5-10-1-16-11	20,386.1
2	13-9-10-1-17-25		9-14-15-1-6-7-8	
3	18-26-29-3-28-30-27		18-12-13-20-2-21-23	
4	19-14-20-2-16-22		26-19-2-17-25-24-22	
5	12-15-2-21-24		29-3-28-30-27	

Table 4. Algorithm comparison.

Algorithm Type	Operation Scheme	Operation Time(s)	Total System Cost (CNY)	Relative Error (%)
Genetic Algorithm	1	33	21,373.2	4.8
	2	34	21,099.3	3.5
	3	31	22,072.3	8.3
Enumeration Method	1	629	20,386.1	—

5.3. Analysis

After running five times and taking the average value, the cost comparison under different numbers of feeder bus routes is shown in Figure 7. With the increase of the number of feeder bus routes, the bus operation cost decreases slightly, the passenger travel cost increases slightly, and the total cost of the system decreases slightly, but on the whole, the fluctuation of each cost is small. As far as the case itself is concerned, the six routes make the number of stations connected by each route too small, which is inconsistent with the actual situation of the bus in the road network. To sum up, this shows that the number of routes has an impact on the feeder system, but the impact is not significant. At the same time, it proves that it is reasonable and feasible to select five routes for the feeder bus in this case.

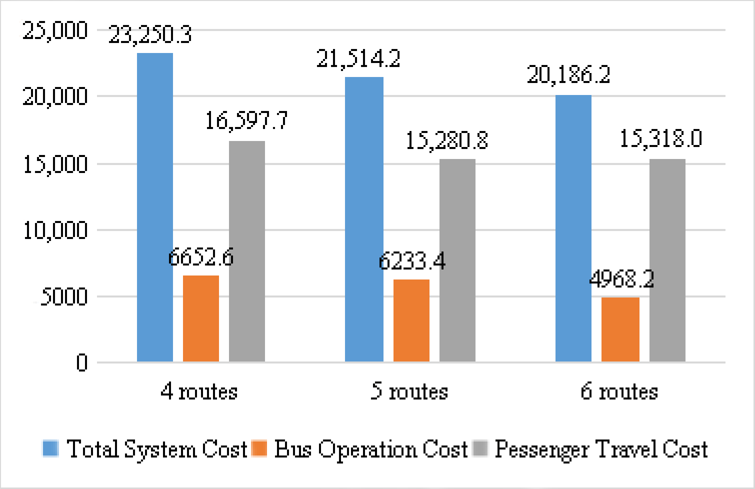


Figure 7. The Cost Comparison under Different Number of Feeder Bus Routes.

For the feeder route optimization scheme and the existing bus route scheme under the same demand conditions, the passenger flow, bus operation cost and passenger travel cost are compared as shown in Table 5.

Table 5. Bus operation and passenger travel costs with and without optimization.

Route Number	Route		Bus Operation Costs (CNY)		Passenger Flow Demand (Person)		Passenger Travel Costs (CNY)	
	Route Optimization	Existing Bus	Route Optimization	Existing Bus	Route Optimization	Existing Bus	Route Optimization	Existing Bus
1	4-5-1-6-7-8-11-23	5-6-7-8-11-1-10	6221.7	4857.4	785	547	14,877	13,041
2	13-9-10-1-17-25	18-20-2-21-24-25			639	593		
3	18-26-29-3-28-30-27	6-1-15-2-20-19-26			914	652		
4	19-14-20-2-16-22	9-13-14-20			590	414		
5	12-15-2-21-24	17-22-24-27-30			598	554		
total					3521	2760		

According to the data analysis in Table 5, in terms of the overall performance of the region in this case, in the aspect of the number of bus passengers, the number of passengers before optimization is 2760 and after optimization 3521, and the passenger capacity after optimization is 27.6% higher than that before optimization, indicating that the optimization scheme can fully improve the passenger capacity of the feeder bus and ensure the travel demands of passengers and the interests of bus operators. In the aspect of the per capita travel cost of the system, although the total passenger travel cost after optimization slightly increased from 13,041 before optimization to 14,877, the per capita travel cost decreased by 10.6%, indicating that the optimization scheme can guarantee the interests of travelers. To sum up, the feeder bus optimization model established in this study can better meet the travel demands of more passengers and fully improve the overall operation efficiency of the feeder bus system.

In this case, when the number of lines changes, the number of buses will also change. The interval of each bus is related to the number of departure routes. Changing the number of routes will change the total number of buses in the system. The number of lines is also related to passenger flow. When the number of lines is small, the maximum transportation capacity range of each line will increase, which will lead to an increase in passenger flow, and vice versa.

At present, feeder buses are widely used, but they still need to give full play to the advantages of buses and subways to maximize benefits. Compared with taxis and private cars, public transport has a larger carrying capacity, which can save energy and reduce environmental pollution. According to the above case study, if we provide more perfect connection services in the future, we can guide people to choose the environmentally friendly travel mode of public transport. This can not only alleviate the problem of traffic congestion but also cooperate with the government's sustainable development policy to benefit the whole society.

6. Discussion

With the in-depth study of the feeder bus, the many-to-one mode has not met the travel needs of passengers [18], and the many-to-many mode came into being. Therefore, this paper studies the many-to-many mode to meet the needs of passengers from different origins and destinations so as to achieve more convenience and rationalization.

In the traditional study of the feeder bus, the starting point of the feeder bus route is the bus station, and the ending point is usually fixed as the subway station [8,12]. In this paper, the starting and ending points of the feeder bus are not limited to the subway station. The route not only undertakes the task of carrying passengers but also plays the role of transporting passengers so as to form an efficient feeder bus system.

As for passenger travel cost, transfer factors are not considered in some studies on the optimization of feeder bus routes [19], and transfer factors are introduced in other studies, but some tend to reduce waiting time by optimizing walking distance, departure interval and timetable [10,20] so as to reduce transfer cost. Regarding the transfer factors, this paper considers the impact of station transfer and makes it clear that the generation of different route schemes will change the transfer choice, and the transfer at different stations will make the routes of passengers more diversified, resulting in different travel costs. In addition, taking the transfer time as a part, this paper directly restricts the travel cost of passengers and uses the transfer time and times to punish the transfer so as to establish an optimization model to make the feeder bus route more reasonable.

In order to solve the problem of the feeder bus, single-objective optimization and multi-objective optimization models are proposed. In order to solve these models and find the optimal path, various heuristic algorithms and accurate algorithms are developed and used [21–23]. In our paper, the genetic algorithm and enumeration method are used at the same time, and the two algorithms are compared to verify the feasibility of the model. The genetic algorithm with a short running time is adopted. In addition, this paper makes a sensitivity analysis on whether the number of routes affects the feeder bus system and proves the effectiveness and credibility of the case.

7. Conclusions

This paper studies an optimization problem of the feeder bus route related to the subway considering station transfer. The main conclusions are as follows:

The optimization model and algorithm of the feeder bus route related to the subway studied and constructed consider the change of passenger travel time cost caused by the change of the station transfer scheme, consider the penalty of multiple transfer costs, take into account the interests of both bus operators and passengers and can obtain the approximate optimal solution of the feeder bus network after fewer iterations.

This paper compares the optimization schemes of designing four routes, five routes and six routes, which shows that the number of feeder bus routes has little impact on the model, and the five feeder bus routes proposed in the case are effective and feasible solutions.

Compared with the existing bus network, the optimization scheme of the feeder bus network has obvious advantages in improving the passenger-carrying rate, reducing the per capita travel cost and improving the overall operation efficiency of the system. However, the operation cost of public transport increased slightly.

In the case study in this paper, the passenger flow in peak hours is selected for modeling and calculation. In the actual research, it can be seen that the departure interval at peak hours is short and the departure interval at peak hours is long, which can be modified according to the actual changes.

Due to the limitation of investigation resources and research conditions, the selected area for this case analysis is small and does not extend to the whole subway line. In addition, the change of tram speed along the route is not considered, and it is hoped that it can be supplemented in follow-up research. Nevertheless, the general rules of theoretical modeling and algorithm design in this study can still be used as a good reference. In follow-up application research, we can gradually overcome the problem of the small scale of the case object, increase the impact of the tram on the route and continue to improve this research.

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