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DESIGNING CUSTOMISED BUS ROUTES FOR URBAN COMMUTERS WITH THE EXISTENCE OF MULTIMODAL NETWORK – A BI-LEVEL PROGRAMMING APPROACH

ABSTRACT

Customised bus (CB) is a cutting-edge mean of transportation and has been implemented worldwide. To support the spread of the CB system, methodologies for CB network design have been conducted. However, a majority of them cannot be adopted directly for multi-modal transportation environment. In this paper, we proposed a bi-level programming model to fill this gap. The upper-level problem is to maximise the usage of the CB system with the limitation of operation constraints. Meanwhile, the lower-level problem is to capture the traveller's choice by minimising traveller's generalised cost during travel. A solving procedure via genetic algorithm is further proposed and validated via the metro data at Shanghai. The results indicated that the proposed CB route network would attract nearly 5,000 users during morning peak period under the given metro transaction data. We further studied the features of the selected routes and found that the CB network mainly served residence to commercial or industrial parks travellers and would provide travel service with fewer stops, and higher travel efficiency by travelling through expressway.

KEYWORDS

bus network design; customised bus; bi-level programming; genetic algorithm; metro transaction data.

1. INTRODUCTION

With travellers' increasing attention on travel comfort and efficiency, bus transit system becomes less attractive due to long detour distance, inappropriate routes, uncomfortable in-vehicle environment and great dwelling time. These deficiencies lead to the shift of travellers from bus transit to private cars, which further exacerbates traffic congestion, energy consumption and greenhouse gas-emissions. Re-achieving the popularity of public transportation system and mitigating the traffic and environmental pressure caused by vehicle travels become priorities for transportation managers.

In recent years, with the spread of smartphones and the wide spread of internet, an innovative bus transit system, customised bus (CB), has been implemented successfully among cities [1]. This distinctive system analyses passengers' travel requests obtained from online platform and provides user-oriented service by setting up appropriate routes and timetables for passengers with similar origins, destinations, and arrival and departure times [2, 3]. To achieve high quality of service and comfort, the number of intermediate stops of a specific CB route is relatively low and the number of passengers is limited according to the 'one passenger, one seat' rule. These novel features largely improved the popularity of the CB systems. Nowadays, CB has been successfully implemented in more than 30 cities in China including Shanghai, Beijing and Shenzhen [1]. According to related works, the implementation of CB provided high level performance compared with inefficient public transportation system and led to a decrease of private vehicles [3–5].

To achieve the success of the CB system, methodologies on the CB network design were conducted in the past several years [6]. Unfortunately, a majority of them are developed under the assumption that CB is the only travel choice for travellers. The generated network may not meet travellers' requirements under the multi-modal transportation condition due to the market competition between CB and other travel modes.

In this paper, we introduce a CB routes design model for multi-modal travel condition. The model is set as a bi-level mixed integer programming model. The upper-level problem is to select CB routes and bus frequencies to maximise CB usage with the knowledge of travellers' choices, while the lower-level problem is to capture the traveller's choice by minimising traveller's generalised cost during travel. To solve this problem with high efficiency, a heuristic framework via genetic algorithm is further designed. The OD data and travel utility estimated from the smartcard data at Shanghai are utilised for effectiveness evaluation.

The remainder of this paper is organised as follows. Section 2 discusses the current status of CB research. Section 3 introduces the mathematical formulation of the CB routes design problem. The solving procedure is then proposed in Section 4, followed by the case study and discussion based on Shanghai's multi-modal transportation network in Section 5. Finally, the conclusion, limitations and future research directions are discussed in Section 6.

2. LITERATURE REVIEW

To instruct CB adoption and increase its usage among cities, related works were conducted to achieve accurate CB travel demand and generate CB network with high level quality of service.

Travel demand is the basic but most important input in the CB network design. According to Liu and Ceder, 2015 [3], several CB systems in use collected travel origin and destination (OD) information based on the reservations system or online survey, which is inefficient and costly [7]. Research further explored the possibility of acquiring CB demand via other methods of collecting data. Qiu et al. introduced a comprehensive procedure for identifying potential CB users based on bus smartcard data. This method provides guidance to public transit managers for planning reasonable bus lines and allocating vehicle capacities [8]. Similarly, Li et al. provided a methodological framework for potential CB routes extractions consisting of trip reconstruction, OD area division and CB route extraction process. Based on the smartcard data from Beijing, 249 potential CB routes are selected for further evaluation [2]. Cen et al. studied last-mile travel features at suburban metro stations via taxi origin-destination data and developed a sequential grouping algorithm for setting up customised bus for last-mile service, which would decrease the trip cost and mitigate traffic congestions among metro stations [9]. Qian et al. proposed a process for identifying point-to-point CB routes by implementing grey relational analysis method considering travel demand volume and its variation, potential operating cost, and CB time savings. The proposed methodology is then applied to determine potential CB routes as supplementary corridors for metro transit at Shanghai [10].

Based on the traditional transit network design method [11, 12], researchers also proposed a CB route network design method with effectiveness and efficiency. Guo et al. introduced an integer programming model by minimising total user cost and vehicle operation cost [13]. The results illustrated that the designed CB routes could decrease operation cost without compromising various requirements compared with the current transit network. Ma et al. established a model for CB station selecting and timetable setting for the CB system by considering traveller's cost, operation cost and social welfare. An immune genetic algorithm is further proposed for the solving process [14]. Cao and Wang proposed a two-stage process to construct CB routes. The CB routes were planned as the combination of travel demand's shortest paths by considering passengers' travel time, waiting time, penalty of delay and ticket price. This method resulted in a 38.33% reduction in average travel time and waiting time according to the case study [15]. Ma et al. discussed a four-step process for CB network planning, considering OD data merging, CB line OD area division, pairing and routes selection. The routes are estimated by minimising the operating, environmental cost and traffic congestion [16]. Meanwhile, to capture commuters' arrival and departure time requirements, Li et al. proposed a mixed load custom bus routing model for the school bus network design problem considering travellers' time windows. The proposed method led to a 10.35 kilometres routing distance decrease according to the studied case [7]. Tong et al. introduced the space-time prism concept from transport geography and formulated the CB route design problem as a multi-commodity network flow optimisation model. A Lagrangian decomposition algorithm was applied to mitigate computation difficulty [6]. Recently, a bus line planning framework for CB systems considering the mode shift probability was presented by Lyu et al. This framework could provide a systematic perspective in designing CB routes under given multimodal transportation networks [17].

Several studies also considered CB as a composition for combination travel and discussed its possible impact. Zhao et al. discussed the impacts of congestion pricing adoption on bus transit system, to further instruct CB transit network design [18]. Yu et al. proposed a demand-responsive transit circulator service network design method for providing seamless connection between rail station and travellers destination [19]. Oliveira et al. optimised bike-bus network to increase the usage of public transit system and mitigate private vehicle usage [20].

According to the literature review, related works have made progress in improving CB adoption among cities. However, due to the ignorance of competition between CB and other means of transportation, the planned CB routes may not attract enough passengers as predicted due to the market competition between CB and other travel modes in on-site application. Improving the applicability of CB network design method at multi-modal transportation condition would provide substantial help for CB route design, operation and management.

3. METHODOLOGY

To consider the reaction of travellers to the proposed CB routes, the CB route design problem is designed as a leader-follower game [21]. The leader, CB route planner, would set up the CB routes and their frequency to maximise the usage of the CB network with the knowledge of the respondence from travellers, while the followers, commuters, would select their transportation mode and specific route according to the CB network and the current multi-modal network to maximise their travel utility. To capture the relationship of various decision makers, this game is modelled as a bi-level mixed integer programming problem. The upper-level problem is to maximise the number of CB route users considering the constraints of operation cost, route length, capacity, time windows and number of stops. The lower-level problem is to minimise traveller's generalised travel cost, a weighted combination of travel time, ticket fare and in-vehicle congestion level for each OD pair.

3.1 Mathematical notations

The CB system can be described as a directed graph $G=\{N,A\}$ where N and A are nodes and arcs respectively. In this paper, nodes are the combination of origins and destinations of CB routes and an arc is the shortest path between two specific nodes. A specific CB route would be a series of arcs connected sequentially. The notations of parameters and variables relevant to the proposed problem are presented in *Table 1*.

3.2 Mathematical modelling

Upper-level problem

The upper-level problem is to determine the route network of the CB system, the fleet size and ticket fare for each CB route by maximising the number of CB users. The upper-level problem is formulated as follows:

$$\max Z = \sum_{i}\sum_{j}\sum_{k} y_{ij}^{k} \tag{1}$$

subject to

$$\sum_{i}\sum_{j} y_{ij}^{k} p^{k} - \left|\frac{C^{k}}{C}\right|\left(c_{f} + c_{r}\left(\sum_{i}\sum_{j} x_{ij}^{k} t_{ij} + s_{k} t_{d}\right)\right) \geq 0 \quad \forall\, k \tag{2}$$

$$V_{i}^{k} + \sum_{j} x_{ij}^{k} \sum_{j} y_{ij}^{k} - \sum_{j} x_{ji}^{k} \sum_{j} y_{ji}^{k} \leq C^{k} \quad \forall\, k \tag{3}$$

$$V_{o}^{k} = V_{e}^{k} = 0 \quad \forall\, k \tag{4}$$

$$y_{ij}^{k}\left(\sum_{l} x_{il}^{k} \sum_{l} x_{lj}^{k} - 1\right) = 0 \quad \forall\, i,j,k \tag{5}$$

$$\sum_{i \in N \setminus i} x_{ij}^{k} - \sum_{i \in N \setminus i} x_{ji}^{k} = 0 \quad \forall\, j \in N,k \tag{6}$$

$$\sum_{i}\sum_{j} x_{ij}^{k} \leq 1, \quad \forall\, k \tag{7}$$

$$\sum_{i} x_{oi}^{k} = 1 \quad \forall\, k \tag{8}$$

Table 1 – Notations of the BLMIP problem

Sets/Indices	
i, j, l	Indices of nodes
N	Set of nodes in the CB network
k	Route indices
Parameters	
M	The pre-determined maximum number of CB routes
p_{ij}^a	Price of the current travel route from node i to node j
S_k	Number of stops of the kth CB line
F	Maximum number of vehicles for each CB route
P	Maximum number of stops of a CB line
C	Capacity (number of seats) of the CB vehicles
T_{ij}^a	Travel time from node i to node j by the current travel mode
S_{ij}^a	Space of the vehicles in the current travel mode
Q_{ij}	The travel demand from i to j
t_{ij}	Minimum travel time from node i to node j
D_{max}	Maximum length of a CB route
D_{min}	Minimum length of a CB route
a_{ij}	Travel distance from node i to node j
c_f	Fixed labour cost
c_r	Operation cost rate of the CB bus (RMB/km)
VOT	Value of time (RMB/h)
o	Virtual origin bus depot
e	Virtual destination bus depot
t_d	Dwelling time of CB bus at each station
V_i^k	Passenger volumes of the kth line's sth vehicle arriving at the ith node
$\bar{Q}_{ij}^a$	Expected passenger volume from node i to node j of the current travel mode
E_{ij}^a	Equivalent travel time considering in-vehicle congestion from i to j of current travel mode
Decision Variables	
x_{ij}^k	Equals to 1 if the kth CB route travels from i to j without passing other nodes, 0 otherwise
y_{ij}^k	The travel demand that takes the kth CB line from i to j
C_k	Capacity of each CB route
p^k	Price of the rth customised bus route
t_i^k	Arrival time of the kth line at node i

$$\sum_i x_{ie}^k = 1 \quad \forall\, k \tag{9}$$

$$t_{oi} = t_{ie} = 0 \quad \forall\, i \tag{10}$$

$$D_{\min} \le \sum_{ij} x_{ij}^k d_{ij} \le D_{\max} \quad \forall\, k \tag{11}$$

$$\sum_i \sum_k x_{oi}^k \le M \tag{12}$$

$$S_k = \sum_i \sum_j x_{ij}^k + 1 \le P \quad \forall\, k \tag{13}$$

$$x_{ij}^k \left(t_i^k + t_{ij} + t_d - t_j^k \right) = 0 \quad \forall\, i,j,k \tag{14}$$

$$\left| \frac{C_k}{C} \right| \le F \quad \forall\, k \tag{15}$$

$$x_{ij}^k = \{0,1\} \quad \forall\, i,j,k \tag{16}$$

$$p_k > 0 \quad \forall\, k \tag{17}$$

$$t_i^k \ge 0 \quad \forall\, i,k \tag{18}$$

In the upper-level problem, the decision variables are $x_{ij}^k\ \forall i,j,k$, T_k, $t_i^k\ \forall k$, $p_k\ \forall k$. The objective (*Equation 1*) is to maximise the number of CB users. *Equation 2* ensures that the operational cost should not exceed the route profit. *Equation 3* ensures that the number of travellers at each station should not exceed the CB capacity. *Equation 4* indicates that the passenger volume at the origin and destination depot should be zero. This equation is presented for the passenger volume estimation of a specific CB at a given station. *Equation 5* ensures that when a CB route serves a specific OD pair, this CB line should visit both the origin and the destination. *Equation 6* illustrates that vehicles should leave nodes after accessing them. *Equation 7* indicates that each node can be visited by a specific vehicle once. *Equation 8 and 9* ensure that each route should depart from the origin depot and arrive to the destination depot. *Equation 10* means that the travel time from virtual depot to a specific node would not be considered in the travel time estimation process. *Equation 11* is the route length constraint. *Equation 12* limits the number of CB routes. *Equation 13* is the station constraint. *Equation 14* is implemented for timetable estimation. *Equation 15* limits the fleet size of each CB route. *Equation 16–18* are the range constraint for the decision variables.

Lower-level problem

The lower-level problem is to estimate the travel demand of each OD pair. This model is designed based on the assumption that travellers have full knowledge of the CB routes and the corresponding ticket fares and the availability of seats. It should be noted that such information can be easily obtained from the mobile app and online platform nowadays. The details of the lower-level problem are presented below:

$$y_{ij}^{k} \in \underset{i,j}{\operatorname{argmin}}\, C = \sum_{k} y_{ij}^{k}\left(VOT\left(t_{j}^{k} - t_{i}^{k}\right) + p^{k}\right) + \left(Q_{ij} - \sum_{k} y_{ij}^{k}\right)\left(p_{ij}^{a} + VOT \cdot E_{ij}^{a}\right) \quad (19)$$

subject to

$$0 \leq y_{ij}^{k} \quad \forall\, i,j \quad (20)$$

$$\sum_{k} y_{ij}^{k} \leq Q_{ij} \quad \forall\, k \quad (21)$$

$$E_{ij}^{a} = T_{ij}^{a} \cdot f\left(\frac{\overline{Q}_{ij}^{a}}{S_{ij}^{a}}\right) \quad (22)$$

In the lower-level problem, $y_{ij}^{k}\ \forall i,j,k$ is the variable needed to be obtained. The objective function (*Equation 19*) is to minimise the total generalised cost of each OD pair. *Equation 20* is the non-negative limit to y_{ij}^{k}. *Equation 21* is the flow constraint. *Equation 22* is the calculation of equivalent travel time considering the in-vehicle congestion level. The equivalent travel time factor is a function related to the passenger density, which is the division of travel demand and the corresponding space of the transportation mode. It should be noted that the capacity of a specific CB line equals to its seat volume, and the in-vehicle congestion cost is not considered in the lower-level problem.

4. SOLVING PROCEDURE

The bi-level property of the proposed model and the existence of mathematical program with equilibrium constraints (*Equation 5 and 14*) impose great difficulty in the solving process. To achieve robust and good-quality network plan with efficiency, the genetic algorithm (GA) is then adopted for route selection. GA is a heuristic method inspired by the natural selection process and has been widely used in various bi-level transportation problems such as network design, parking management etc. [22, 23].

The proposed solving procedure consists of 2 parts, namely, CB routes generation and CB routes selection. In the CB routes generation section, the CB route is designed as an individual and is generated and updated according to the GA framework by implementing crossover and mutation operation. Then, the acceptable ticket fare would be estimated according to the current generalised travel cost of each OD pair served by the proposed CB route. Given the route information and its corresponding price, the number of passengers served by the route would be estimated by the lower-level problem and the feasibility of the route would be checked according to the corresponding constraints in the upper-level problem. The infeasible solution will be penalised before the implementation of crossover and mutation process. Once the GA framework is terminated, the feasible solution set would be generated and regarded as the input in the route selection section. A knapsack problem is then applied to select the best CB routes according to the maximum number of CB routes. The detailed steps of the solving procedure are presented below:

Step 1: Initialisation. Set up the maximum number of OD pairs a CB line serves (P), population size (P_s), maximum iterations (I), and the probability for the crossover (P_c) and mutation process (P_m).

Step 2: In the first iteration (i=1), for the kth individual, randomise a digit (P_i) ranged from 1 to P as the number of OD pairs that the individual line serves. Pick up P_i OD pairs sequentially from the OD set and set up the stop sequence according to the OD pair order. The chromosome of each individual is the stop series shown in *Figure 1*. The greater than 0 digits are the stop indices while digit 0 indicated the empty property of the gene. According to the stop series, generate the CB line with the shortest path of each two connected stops. Check the route length and calculate the arrival time of each stop. Estimate the minimum p^k for each OD pair by using *Equation 23*. Evaluate the passengers served by the kth individual using the lower-level problem and check the line's feasibility by *Equation 2–5*. If the route length does not satisfy *Equation 11* or the route does not satisfy *Equation 2–4*, the fitness of this individual is posed as 1. Otherwise it is posed as the total number of passengers served by this individual plus 100. The feasible solution would be stored in the feasible set for further estimation.

$$VOT\left(t_{j}^{k} - t_{i}^{k}\right) + p^{k} \leq p_{ij}^{a} + VOT \cdot E_{ij}^{a} \quad \forall\, x_{ij}^{k} \quad (23)$$

Stop sequence	1	2	3	4	5	6	···	···	···	···	···	···	···	···	N-1	N
Chromosome	5	1	18	27	6	2	...	...	...	...	...	0	0	0	0	0

Figure 1 – The chromosome structure of the individual

Step 3: Applying the roulette method for picking up individuals for crossover and mutation process. The probability of the kth individual and its corresponding cumulative probability can be estimated according to *Equation 23* where $f(x_k)$ is the kth individual's fitness and $p(x_k)$ is its corresponding picking up probability.

Carry out the crossover operation and mutation operation sequentially according to their corresponding probability. This technique would expand the search region to achieve better results. It should be mentioned that the updated individuals who fail to satisfy the maximum number of OD pairs would be abandoned in the following process. Once the number of feasible updated individuals reach the designed population, i=i+1. If i does not reach the predetermined level, return to Step 2. Otherwise, terminate the GA process and go to Step 4. Generate the feasible CB route set.

$$p(x_k)=\frac{f(x_k)}{\sum_k f(x_k)} \tag{24}$$

Step 4: The feasible CB route set is implemented to the lower-level problem to estimate the passenger volume each CB route serves under the configuration of current travel mode. The top M routes with the highest passenger volume would be regarded as the final plan for the proposed model.

5. CASE STUDY AND DISCUSSION

5.1 Input data and data processing

To validate the effectiveness of the proposed methodology, a case study is designed based on the metro transaction data (MTD) and open-source road network data in Shanghai, China. The MTD is applied to calculate the city's OD information and to estimate travellers' generalised cost when using metro system. Meanwhile, the open-source road network data from Gaode API is proposed for CB travel time estimation of each OD pair [24]. Given these inputs, the solving procedure is further implemented for selecting competitive CB routes for this case study. The flow chart of the data processing and CB routes generation procedure is illustrated in *Figure 2*.

The data processing and solution generation procedure can be divided into three parts: trip reconstruction, OD aggregation and CB routes generation and selection. For trip reconstruction, the transaction data for each metro user is extracted via

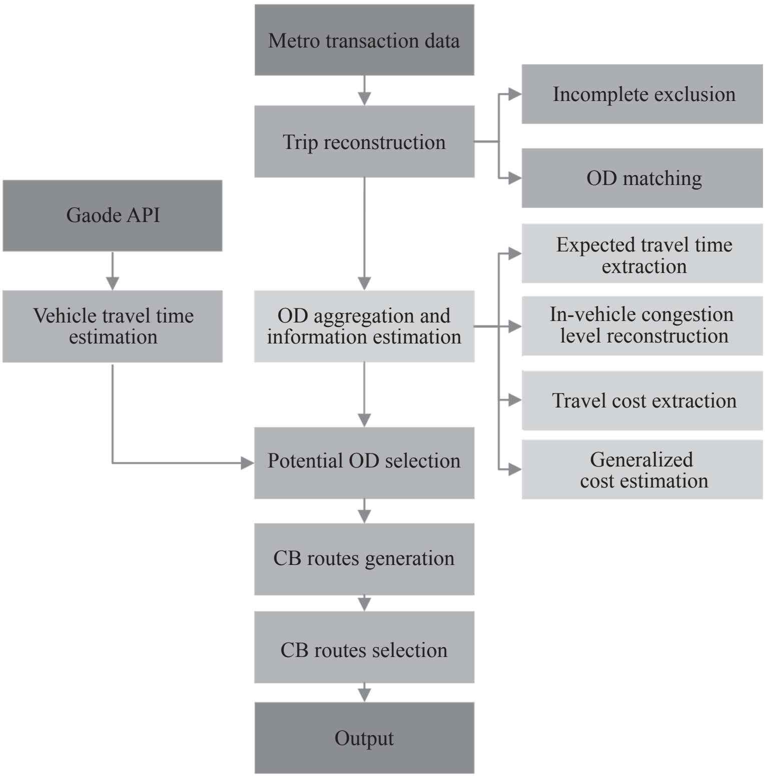

Figure 2 – The data processing and CB routes generation procedure

unique travel ID. The OD information is matched according to the transaction order. With the discrete trip information, the travel demand for each specific OD pair is then aggregated. According to the aggregation set of a specific OD pair, the expected travel time (the 85 percentile travel time) and expected travel cost can be further estimated. The travel demand that each metro served is then estimated by using the Dijkstra algorithm based on the OD data [25]. Finally, the generalised costs of metro travels are presented as the weighted combination of travel cost, travel time and congestion level. In the CB routes generation and selection part, the vehicle travel time for each OD pair, regarded as the CB travel time, is achieved from Gaode API. Based on the minimum CB travel time and the current generalised cost, the OD pairs are further selected according to the number of travel demand and their potential utility gains from CB system. The route generation process via GA and the lower-level optimisation process are implemented to achieve the final output.

5.2 Data processing result of MTD

The metro system in Shanghai is worldwide famous due to its greatest mileage. This system is built with over 500 km rail lines, containing 288 stations and 14 lines according to the information from Shanghai Shentong Metro Group Operations Management Department in 2015 [26, 27]. The network structure of the Shanghai metro network and the entrance and exit demand of each station during morning peak period (8:00:00 a.m. to 9:00:00 a.m.) on an ordinary workday (14 April 2015) is presented in *Figure 3 and 4*. According to the entrance demand pattern in *Figure 3*, a great proportion of commuters live outside the centre area of Shanghai, and diversely spread among the

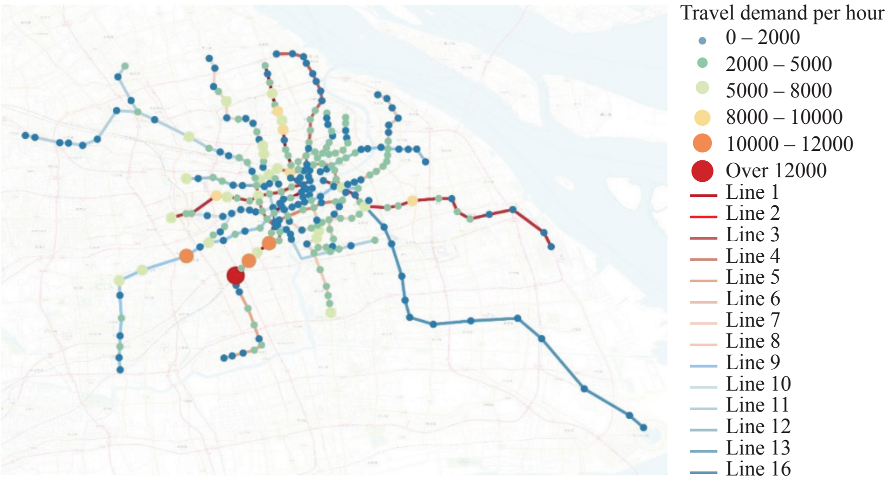

Figure 3 – Entrance demand of metro stations during morning peak period

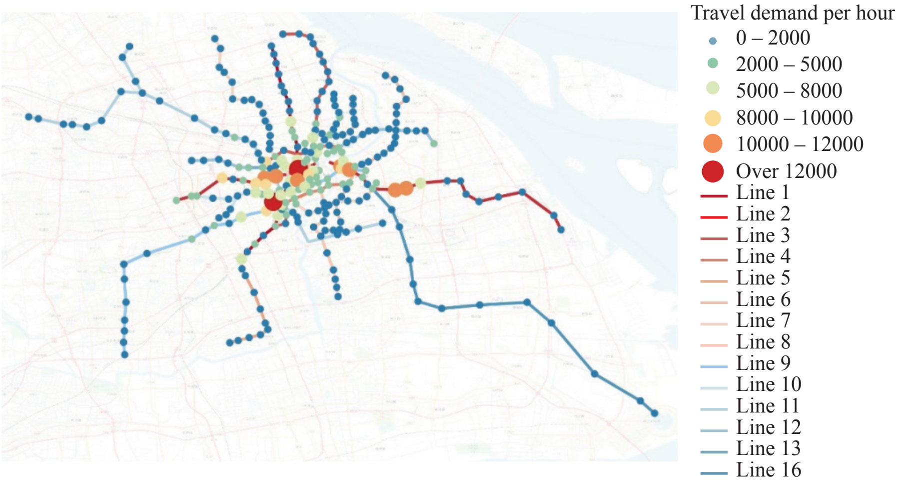

Figure 4 – Exit demand of metro stations during morning peak period

outside area. A majority of them would commute to the Shanghai central business district in the Puxi area, leading to the exit congestions at some hot metro stations in *Figure 4*.

The MTD is obtained on 14 April 2015 with more than 9 million tap-in/tap-out records. A record is generated once passing the entrance/exit gate at a station and is a composition of trade time, trade location, line ID and price. The OD data is reconstructed according to the details in the previous content. Based on the transaction data acquired between 8:00 a.m. and 9:00 a.m., 620,866 travel demands were extracted, unevenly distributed within 44,781 OD pairs. A majority of the OD pairs are with less than 300 people per hour travel demand. However, some exceptions do exist with over 1,000 travel demands during peak hour. These OD pairs distribute diversely in the Shanghai city but a great proportion of them exist in the centre area. For the travel time features, the travel time between metro OD pairs lies in the range from 3 minutes to 90 minutes, which is similar to the travel time range by vehicle.

The metro network topology, timetable and space of each metro line are collected from the Shanghai metro website [28]. Based on these details, the passenger density of each metro link is estimated by implementing the Dijkstra algorithm. Each metro link's average passenger density level varies between 0.04 and 5.20 people/m^2. With these data, the generalised cost (G_{ij}^a) of each OD pair using metro travel mode is calculated via *Equation 25*, where VOT is set to be 34 RMB per hour and α, β equal to 0.1251 and 0.8226 respectively according to the survey results in Beijing from Fang et al. [29]. The distribution of the generalised cost is presented in *Figure 5*. The generalised commuting cost during morning peak period distributed within the range of 4.15 RMB and 66.29 RMB and nearly 60% of the samples lie between 20 RMB and 40 RMB. The average generalised commuting cost for each traveller is 30.7 RMB which is relatively large considering the high convenience level of the metro system. This phenomenon may be due to the great congestion level occurring in the morning peak period.

$$G_{ij}^a = p_{ij}^a + VOT \cdot T_{ij}^a \cdot \max\left(1, \alpha \cdot \frac{\overline{Q}_{ij}^a}{S_{ij}^a} + \beta\right) \tag{25}$$

5.3 Results and discussion

With the generalised cost via metro system and the minimum vehicle travel time obtained from Gaode API, the upper limit of passenger surplus via the CB system for each OD pair (noted as p_{ij}^u) can be estimated by *Equation 26*. This indicator evaluated the potential profitability and runnability of CB routes for a specific OD pair. To simplify the CB route generation process, OD pairs with travel demand greater than 10 people per hour and with p_{ij}^u over 10 RMB are selected as the potential OD set for CB generation. There are 3,286 qualified OD pairs selected for further estimations. The parameter settings for CB routes generation and selection are presented in *Table 2*.

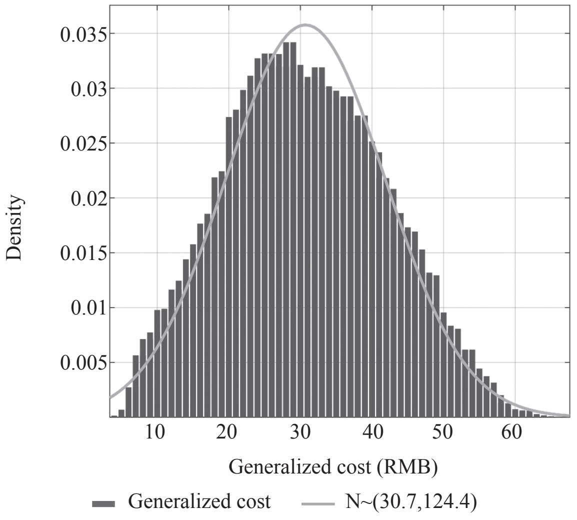

Figure 5 – The distribution of generalised commuting cost during morning peak period

$$p_{ij}^u = p_{ij}^a + VOT \cdot T_{ij}^a \cdot \max\left(1, \alpha \cdot \frac{Q_{ij}^a}{C_{ij}^a} + \beta\right) - VOT \cdot T_{ij} \tag{26}$$

Based on the pre-determined inputs, 52,282 feasible routes are generated from the proposed methodology. The information of the selected 10 CB routes leading to maximum CB usage is presented in *Table 3* and *Figure 6*. The fares of the selected CB routes ranged from 7 to 11 RMB, which is higher than the metro travel cost (normally 3 to 8 RMB). The number of stops of the generated 10 routes ranged from 2 to 4 stops, which is lower than the pre-determined maximum number of stations. This may be due to the negative effect of detouring distance and extra operation cost when setting up extra stations. Meanwhile, the travel range of CB routes varied from 5 to almost 40 kilometres. Although line 1 is not within the economic range of the bus system and the travel time is relatively long, the route would be popular since travellers would not suffer transfer and in-vehicle congestion during peak period compared with metro travel. The rest of the routes provided long-range service with high level of travel comfort for commuters.

Table 2 – Parameter settings for the case study

Notations	Meaning	Settings
	Input settings	
M	The maximum allowed number of routes of the CB network	10
F	Maximum number of vehicles for each CB route	4 vehicle/hour
P	Maximum number of stops of a CB line	5 Stops
C	Capacity (number of seats) of the CB vehicles	40 seat/vehicle
D_{max}	Maximum length of a CB route	40 km
D_{min}	Minimum length of a CB route	5 km
VOT	Value of time (RMB/h)	34 RMB/h
t_d	Dwelling time of CB bus at each station	1 minute
c_f	Fixed labour cost	80 RMB
c_r	Operation cost rate of the CB bus (RMB/h)	132 RMB/h
	GA settings	
P_s	Population size	5000
I_m	Maximum iteration	200
P_c	Crossover probability	0.3

Table 3 – Information of the selected CB routes

ID	Fare (RMB)	Operation cost (RMB/vehicle)	Distance [km]	Travel time [min]	Potential demand	Maximum number of transfers via metro transit	Route
1	11	91	5	17	721	1	South Huangpi Road – Lujiazui
2	11	113.22	15.1	29	535	1	Jufeng Rouad – Guanglan Road – Jinke Road
3	10	156.12	34.6	60	507	1	South Qilianshan Road – South Shanghai Station – Middle Yangao Road
4	12	144.68	29.4	62	486	1	Pusan Road – Huamu Road – East Nanjing Road
5	11	140.5	27.5	58	473	0	Anshan Xincun – Shendu Gonglu
6	10	128.84	22.2	64	454	2	North Zhongshan Road – Caohejing Development Zone – Songhong Road
7	9	150.4	32	54	437	2	Shendu Gonglu – Caohejing Development Zone – Daduhe Road
8	7	127.08	21.4	56	431	1	Gongkang Road – Loushanguan Road – Caohejing Development Zone
9	11	125.1	20.5	42	425	1	Huangxing Road –Middle Yanggao Road – Zhangjiang High-tech Zone – Longyang Road
10	8	165.58	38.9	62	414	1	Caobao Road – Jinke Road – Wujiaochang

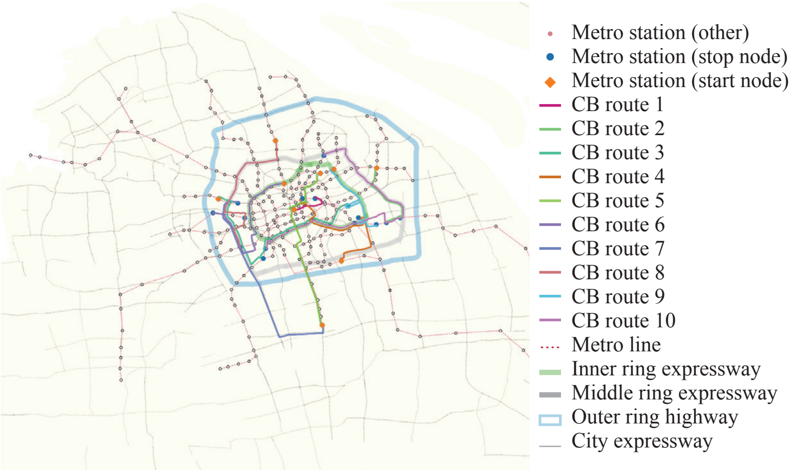

Figure 6 – Visualisation of the proposed CB routes

These results indicate that the proposed model could generate routes for various travel services such as point to point short-term travel and long range travel.

To further discuss the features of the selected CB routes, the details of each travel route, along with the rail transit station it served and the city expressway topology of Shanghai, is presented in *Figure 6*. As seen in the figure, 9 of the 10 CB routes started within the Outer Ring Highway of Shanghai. This result seemed to be reasonable since the travel demand outside the outer ring is not sufficient for the CB operation. Meanwhile, according to the travel demand features of the metro stations, most of the selected CB routes would start near large residential areas, such as Anshan Xincun, Huangxing Road and stop at commercial and industrial parks, namely, Lujiazui, Caobao Road, Caohejing Development Zone and Zhangjiang Hi-tech Zone. The maximum number of transfers for the potential CB travellers when using the metro system is collected and only several OD pairs would experience more than once transfer during travel. We've further checked the routes each CB route selected and we figured out that all of the CB routes operated via expressways. These results suggested that the competitiveness of the CB routes is not mainly due to the avoidance of transfers but the decrease of travel stops, travel detour and the increase of travel efficiency through expressway.

6. CONCLUSION AND FUTURE RESEARCH

With the application of smartphones and online apps, customised bus, a novel demand-responsive transit system, has been implemented in cities of China. The limited number of intermediate stops and ‘one passenger, one seat’ rule lead to the increasing popularity of the CB system compared with the current bus transit. Due to these novel features of the CB system, methodologies for designing CB routes and the corresponding solving framework have been proposed. Unfortunately, a majority of them are developed under the assumption that the CB is the only travel choice for travellers. The proposed CB route network may not be that attractive due to the competition with other travel modes. To improve the applicability of the CB route design method, we formulated the CB route design problem as a bi-level programming problem and proposed a GA based solving procedure. The proposed methodology successfully captured passenger shift from current travel mode to the CB system by estimating the choice behaviour of travellers according to a generalised travel cost. It also provides suggestions for route capacity and route pricing settings. A case study based on the MTD and network configuration of Shanghai is proposed for model validation. The proposed CB route network would attract nearly 5,000 users per day. We further studied the travellers CB routes served and the competitiveness of route patterns. The CB routes were mainly designed for residence to commercial or industrial parks travellers. And the attractiveness of CB routes may largely be due to its fewer stops, less travel detour property and the increase of travel efficiency by travelling through expressway. These results illustrated that the proposed methodology can generate feasible CB routes for multi-modal transportation environment.

Similar to other studies, this research has its own limitations. The proposed model is with static feature and fails to consider the choice behaviour through time. It cannot consider the penalty of early travelling due to inappropriate timetabling. This would be the direction of our future study. Moreover, an innovative algorithm to solve the CB route design problem would offer great efficiency and should be considered in the future.

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面向多模式交通网络的定制公交设计：一种双层规划方法

摘要

定制公交是一种新型交通模式并已在全世界推广。为支持其发展，定制公交网络设计方法被普遍提出。然而，多数方法在多模式交通出行场景下适用性较弱。本文提出了一种基于双层规划的定制公交网络设计方法，上层模型在考虑定制公交运行约束的基础上，实现定制公交系统出行人次最大，下层模型以用户广义出行成本最小为目标获取用户出行选择方案。论文进一步提出了基于遗传算法的求解方法，并利用上海市地铁交易数据开展案例分析。案例中，生成的定制公交网络将吸引超过*5000*人次的出行需求。同时，定制公交线路多服务于住宅至工商业园区出行者，且线路站点少，多基于城市快速路运营，保证了出行效率。

关键词

公交车网络设计；定制公交；双层规划；
遗传算法；地铁交易数据

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