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Optimal Express Bus Routes Design with Limited-Stop Services for Long-Distance Commuters

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Abstract: This research aimed to propose a route optimization method for long-distance commuter bus service to improve the attraction of public transport as a sustainable travel mode. Taking the express bus services (EBS) in Changping Corridor in Beijing as an example, we put forward an EBS route-planning method for long-distance commuter based on a solving algorithm for vehicle routing problem with pickups and deliveries (VRPPD) to determine the length of routes, number of lines, and stop location. Mobile phone location (MPL) data served as a valid instrument for the origin–destination (OD) estimation, which provided a new perspective to identify the locations of homes and jobs. The OD distribution matrices were specified via geocoded MPL data. The optimization objective of the EBS is to minimize the total distance traveled by the lines, subject to maximum segment capacity constraints. The sensitivity analysis was done to several key factors (e.g., the segment capacity, vehicle capacity, and headway) influencing the number of lines, the length of routes. The results suggest that the scenario with the segment capacity of 4000 passengers/h has a minimum of number and length of lines, but we recommend that the transit agency adopt 3000 passengers/h as the route segment capacity because this scenario results in minimum fleet size and minimum total operation length.

Keywords: bus route optimization; express bus service; VRPPD; long-distance commute; mobile phone location

1. Introduction

With four decades of economic development and urban population growth, Beijing, like other megacities in China, has experienced enormous sprawl and urban development [1,2]. The Beijing metropolitan area has formed a unique spatial structure with six concentric ring roads. An increasingly large number of low- and middle-income workers are living in the city fringe, whereas most of their jobs are in the inner area of Beijing [3–6]. The imbalance has led to increasing demand for long-distance centripetal commuting trips (i.e., trips from peripheries to the center) in morning peak hours [7,8], which places significant pressure on the transportation infrastructure [9,10]. During the morning peak-hour ridership of subways, trains running suburban districts are extremely overloaded. Taking Changping Corridor as an example, both the subway (Lines 5, 8, 10, 13, and Changping Line) and the arterial roadways (Highways G6 and G7) have severe congestion in the morning. Given the high cost of expanding infrastructures such as subways and roadways, the public has suggested new bus services for long-distance centripetal commuters, which would meet the excessive demand and relieve the pressure on rail transit and roads.

Recently, the government has been discussing innovative approaches such as customized buses and rapid commuter buses. Particularly, an express bus service (EBS) has been proposed to link Changping District and the inner city. According to the plan, EBS should be similar to bus rapid transit (BRT) under the standards of the Institute for Transportation and Development Policy. Nevertheless, because it only serves long-distance commuters, it would have fewer stops than normal BRTs and the service hours would be between 7 and 9 a.m. A dedicated lane would be provided on Highway G6 connecting Changping and the inner city. Additionally, the agency has considered using feeder shuttles to collect passengers. EBS is expected to provide affordable express services to low- and middle-income workers who commute in Changping Corridor. Given these requirements, EBS would be more sensitive to demand than local buses. Because of the huge travel demand in Changping Corridor, routes design is very important to meet the demand and improve the level of service. In this paper, we aim to design EBS routes with limited-stop services for long distance commuters in Changping Corridor.

Black [11] first mentioned the concept of limited-stop operations, where selected stations were skipped by some vehicles. Limited stop services have been operating in cities like Bogota, Chicago, Montreal, New York City, Santiago. For users, limited-stop services mean improved service levels in the form of lower travel times due to fewer stops and higher between-stop speeds, while for system operators they enable demand to be met with fewer vehicles thanks to shorter bus cycles. This paper addresses the limited-stop service, where different routes serving the corridor may have different stopping plans. That is, our objective is to determine: (a) number of lines, the start station, the destination station, and stops for all EBS lines; (b) the optimal segment capacity, bus capacity, service frequency and fleet size for all EBS lines. To the best of our knowledge, no previous studies in the literature have considered combining the stop service and the routes planning problems together. This study fills this gap.

The remainder of this paper is organized as follows. Section 2 reviews the existing work related to this study. Section 3 presents the two methods, the origin–destination (OD) estimation method based on mobile phone location data and mathematics' model of route optimization for EBS based on a solving algorithm for vehicle routing problem with pickups and deliveries (VRPPD). Section 4 conducts the case study of the Changping Corridor, and the sensitivity analysis was done to the several key factors (e.g., the segment capacity, vehicle capacity and headway) influencing the number of lines, the routes length and the total operation mileage. Finally, Section 5 concludes this paper and limitations of the method are discussed.

2. Literature Review

The design of limited-stop transit service has aroused wide attention. Ceder and Wilson [12] summarized the route-planning process as a five-step systematic decision sequence involving network design, setting frequencies, timetable development, scheduling, and driver scheduling. They also discussed the bus route planning problem that minimizes total system operation costs as an optimization objective. There are two general objective functions considered in previous research for limited-stop design problems, which are to minimize passenger travel time and operator costs. Some researchers considered the minimization of passenger generalized travel time, such as Lee et al. [13], Chiraphadhanakul and Barnhart [14], Niu [15], Sun and Hickman [16], Chew et al. [17]. Some researchers used the objective function: minimizing the operator costs alone, such as Lin and Ku [18]. Most researchers considered minimizing both the passenger and operator costs (Larrain et al. [19]; Leiva et al. [20]; Cao et al. [21]; Chang et al. [22]; Chen et al. [23]; Fu et al. [24]; Larrain et al. [25]; Liu et al. [26]; Chen et al. [27]; Wang et al. [28]. In this study, we had three objectives. From the consumers' perspective, our objective was decreasing the travel time by offering the nonstop or limited-stop express transit service between these big districts; from the governor's perspective, our objective was to shift passengers from existing modes to EBS lines by saving more time than other travel modes; from the operators' perspective, to simplify the process of solving the optimization problem, our objective was minimizing the total length of EBS lines.

Vehicle capacity is considered as a constraint to determine the prime decision variable bus stop selection. Larrain et al. [19] proposed the methodology to select optimal express services for a bus corridor with capacity constraints considering various demand criteria. Leiva et al. [20] presented an optimization approach to design a limited stop service with capacity constraints. Wang et al. [28] formulated a design limited stop service operation strategies as a Mixed Integer Nonlinear Program (MINLP) with vehicle capacity equilibrium constraints. In this study, we consider the segment capacity of the EBS line as a constraint to design routes. Segment capacity of the EBS line is determined by the bus vehicle capacity and departing frequency, and it is a product of vehicle capacity times frequency.

Recently, Genetic algorithms have been widely utilized to find optimal solutions for transit route planning [13,15,18,23,26,29–33]. Other meta-heuristics such as the tabu search method [21] and the artificial bee colony algorithm [27] were also adopted. More recently, 0–1 integer [34], mixed integer linear [35], and nonlinear [28] programs have received attention. Nagy and Salhi [36] proposed a heuristic algorithm for multiple-depot route planning called vehicle routing problems with pickups and deliveries (VRPPD), which can be used to solve a set of optimized routes with certain travel demand, route capacity, vehicle capacity, and time windows. Some software, such as *VrpPd*, can provide solutions for these problems based on an adaptive large neighborhood search (ALNS), a general heuristic algorithm [37]. This VRPPD problem and solution algorithm provides a good way to solve EBS routes planning problem. This study proposes a modified solving algorithm for VRPPD to design the EBS lines and determine the start terminal, the destination terminal and stops for all the EBS lines with the minimizing total distance traveled by the lines.

3. Method

This section mainly introduces two methods, one is OD demand analysis, and the other is design optimization for the EBS lines. We collect the OD distribution of centripetal travel along the Changping Corridor, mainly using the mobile phone location (MPL). Based on travel distribution, we use the improved optimization algorithm for the design of EBS routes with the segment capacity constraint to determine start stations, end stations and the stops of EBS lines based on the solution algorithm for VPRRD problem.

3.1. Demand Data Estimation

The purpose of obtaining the travel distribution data is to serve as the basis of the design of EBS lines. Optimal EBS routes provide passengers with services similar to customized public transport. Passengers can reserve their seats of the EBS line through the website or mobile app, and they take EBS bus vehicles on the designated stops to quickly arrive at the destination zone and take walking or bike-sharing to arrive at the workplace. This study suggests that mobile phone location (MPL) data are analyzed to identify the origins (i.e., living places) and destinations (i.e., workplaces) of commuting trips. The data were attained from China Mobile (CM), the biggest carrier in China. In April 2016, CM had 835 million subscribers, accounting for more than 60% of the population in China. Given this proportion, we estimated that more than 15 million CM subscribers live and work in Beijing. The cellular network of CM includes 38,000 cell sites distributed throughout Beijing. Thus, the average density of the cell sites should be 44 cells/km^2 in urban areas and 2.3 cells/km^2 for the entire metropolitan area (Figure 1). In other words, the service area of each CM cell site in Beijing is about 22,700 m^2 (5.6 acres) on average. Cell sites connect phones via cell signals when phones are in their service area. Each cell site has a unique ID in the cellular network of the city.

Whenever a subscriber uses a mobile phone (e.g., making a call, sending or receiving messages, using the Internet) or moves from one service area to another, a pair of numbers—the subscriber's ID and the cell site ID—is uploaded to the data collection center. Moreover, even if the subscriber does not use the phone, the signal data are still uploaded at set intervals. Based on this mechanism, assuming that when a user travels from Point i to Point j, which are located in service areas of Cell Site A and Cell Site B, respectively, two pairs of location data of A and B are attained by the data collection center at the beginning and end of the trip. Hence, A and B can be regarded as the origin and destination of this trip. If A and B are in TAZs m and n ($TAZ_{(m)}$, $TAZ_{(n)}$), the OD of this trip can be denoted as $TAZ_{(m)}$ and $TAZ_{(n)}$ (Figure 2).

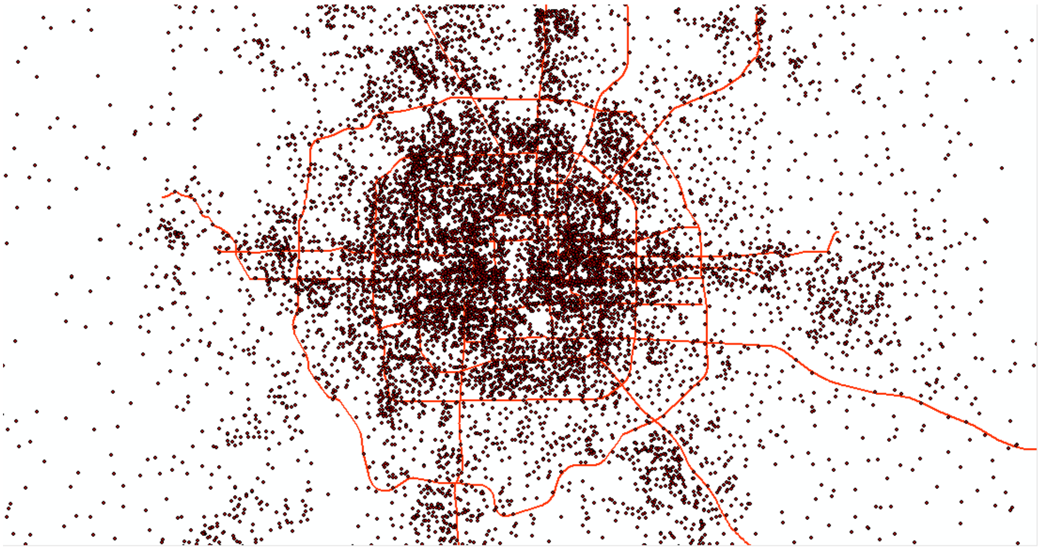

Figure 1. The distribution of cell sites of China Mobile in Beijing.

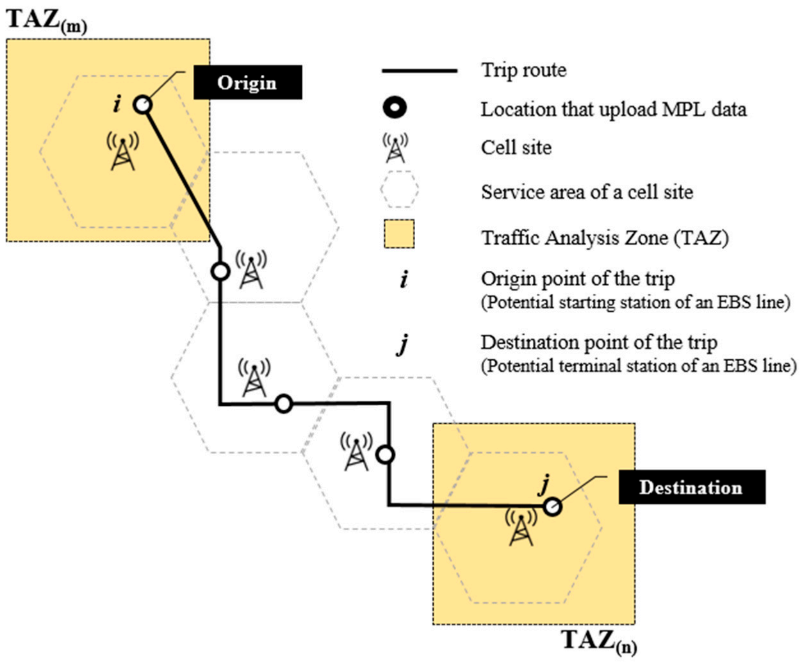

Figure 2. The logic of origin–destination (OD) estimation based on mobile phone location (MPL) data.

Some ways of inferring the home and workplace locations have been proposed in quite a number of studies [38,39]. We collected MPL data during five successive weekdays from Monday. To protect users' privacy, the identification information of CM subscribers was encrypted through a pseudo-ID. Using this logic, MPL data from a 5-weekday period were geocoded to identify CM users' residences and workplaces. That is, if a subscriber stayed in the service area of a certain cell site for at least 3 nights (10 p.m. to 6 a.m.) during the period, we designated this cell site as the user's residence. If the user stayed in the service area of a certain cell site during the daytime (10 a.m. to 4 p.m.) for at least three days, we designated this cell site as the user's workplace. Every OD point associated with a certain cell site in certain segments of the corridor was regarded as an origin or destination inside the segment. The evidence of OD estimation based on the mobile phone data help us precisely decide the number of potential passengers of the EBS. People with changing workplaces such as police or hawkers were excluded in this study since their mobile phone signals could not be consistently identified at a fixed location between 10:00 a.m. and 4:00 p.m. OD distributions of the sample were aggregated and categorized into six segments by the geographic locations defined by Beijing's Ring Roads System:

1. In the 2nd Ring (abbreviated as "S1")
2. Between the 2nd Ring and the 3rd Ring (abbreviated as "S2")
3. Between the 3rd Ring and the 4th Ring (abbreviated as "S3")
4. Between the 4th Ring and the 5th Ring (abbreviated as "S4")
5. Between the 5th Ring and the 6th Ring (abbreviated as "S5")
6. Beyond the 6th Ring (abbreviated as "S6")

Larrain et al. [19] observed that a crucial parameter for determining the potential benefits of express services is the average trip length along the corridor. To specify potential passengers of the EBS, this study subsampled long-distance commuters (their commuting distance >15 km.) in the Changping Corridor. The main reason is following.

The average speed of cars is 14.9 km/h in peak hours [40]. The average speed of four BRT lines is 27, 23, 24, and 26 km/h (shown in Table 1). By definition, EBS should be slightly faster than BRT. Thus, we assume that the speed of EBS is 30 km/h. The travel time by EBS is the sum of the access time from home to the boarding EBS station, the waiting time at the boarding EBS station, the egress time from the destination EBS station to the workplace and the in-vehicle time. In this study, we estimate the approximate access and egress times based on the distances between the EBS stations and residential/employment locations. The distance between the ending station (the 2nd Ring) and the employment hub of the inner city is around 0.5 km, and the average walking speed is about 4 km/h. Therefore, we assign the average egress time as eight minutes. The access time is likely longer than the egress time since the residential locations are more dispersed. Therefore, we assign the average access time as 10 min. The average waiting time is assigned as two minutes based on the common frequency.

Table 1. Operation statistics of four bus rapid transit (BRT) lines in Beijing.

No.	Length of Line (km)	Number of Stations	Number of Intersections	Station Spacing (m)	Speed (km/h)	Maximum Segment Ridership (Passengers/h)
1	15.65	17	22	978	27	6009
2	16.00	20	21	842	23	2312
3	22.95	23	18	1043	24	3366
4	25.50	19	15	1417	26	2116

When the distance of two EBS stations is 15 km, the in-vehicle time is about 30 min, and the total travel time by EBS is about 50 min. The in-vehicle time by cars is about 1 h, so the travel time by EBS is less than the travel time by cars. So the longer distance between two EBS stations, the more travel time saved by EBS with comparison to cars. We extract OD samples with a travel distance of more than 15 km in order to make EBS more attractive. The number of long-distance commuters was 21,478, accounting for 47.55% of all CM subscribers in the corridor. Figure 3 shows the potential EBS passengers' OD distribution.

3.2. *Mathematics' Model of Route Optimization for EBS*

The purpose of EBS routes design is to determine the number of EBS lines and their start and ending station for every line among the set of {S1, S2, ... , S5, S6}. As mentioned before, to simplify the process of solving the optimization problem, our objective was minimizing the total length of EBS lines.

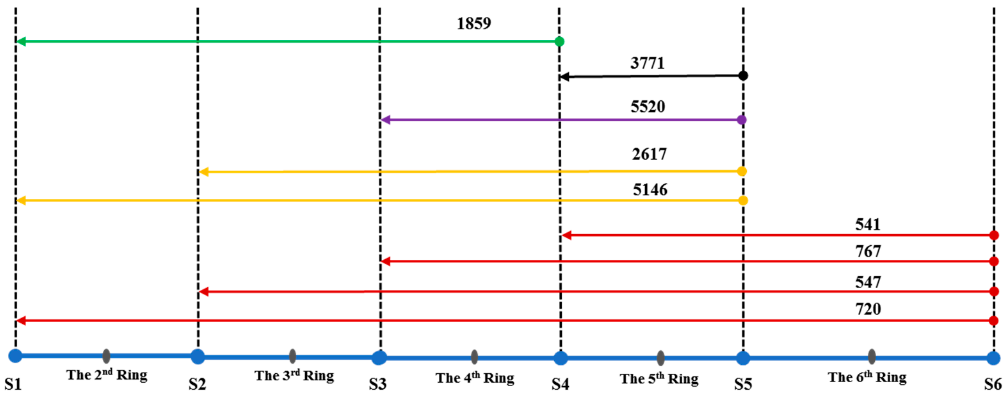

Figure 3. Potential express bus service (EBS) passengers' OD in the Changping Corridor (units: passengers/h).

VRPPD is a problem where the service required by customers may be both the pickups and deliveries of commodities. The goal is to find optimal routes for a fleet of vehicles to visit the pickup and delivery locations. The delivery network for the VRPPD with two depots is shown in Figure 4. The objective function of VRPPD is to minimize the total distance traveled by the vehicles, subject to the maximum distance and maximum capacity constraints on the vehicles [36]. Where EPS lines may both pick up and drop off passengers at EPS stops. We regard the EPS problem as a special example of the VRPPD, and the difference is that EPS problem emphasizes transit lines location planning and VRPPD emphasizes vehicle routes planning. Six segments of Changping Corridor are initialized as depots and EBS stops, these stops have the demand of pickup and delivery. EBS line is treated as the 'vehicle' of VRPPD and it has a segment capacity constraint, the segment capacity is determined by the bus vehicle capacity and departing frequency. The EBS routes optimization problem is to determine the start segment, the destination segment and stops for all the EBS lines with the minimizing total distance traveled by the lines. Figure 5 shows a schematic diagram of the EBS lines optimization results.

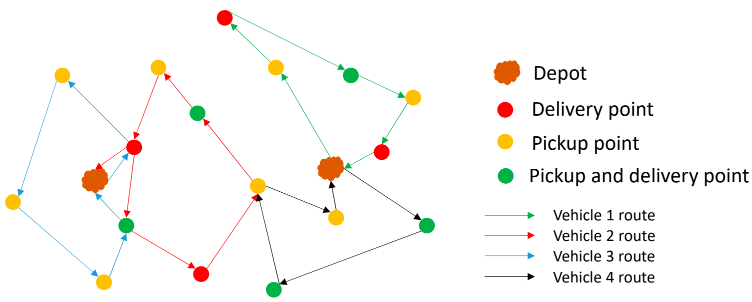

Figure 4. Schematic diagram of the VRPPD.

Following the terminology of Desaulniers et al. [41] and Pisinger and Røpke [37], a problem instance of the pickup and delivery problem contains n requests (or orders) and m vehicles. We regard these segments of travel demand as nodes, EBS lines as vehicles, and OD travel distribution between segments as requests (or orders). The EBS Lines Problem with Pickups and Deliveries (EBSLPPD) is defined on a graph where $P = \{1, \ldots, n\}$ is the set of pickup segments, and $D = \{n + 1, \ldots, 2n\}$ is the set of delivery segments. Request i is represented by segment i and $i + n$. $K = \{1, \ldots, m\}$ is the set of all EBS lines; one line might not be able to serve all requests. These kinds of limitations are modeled by letting $P_k \subseteq P$ and $D_k \subseteq D$ be the set of pickups and deliveries that can be served by line k. Since every request is serviced by the same line we may assume that $i \in P_k \Leftrightarrow i + n \in D_k$, i.e., that both the pickup and delivery can be serviced by line k. Define $N = P \cup D$ and $N_k = P_k \cup D_k$. Let $\tau_k = 2n + k, k \in K$ and $\tau_k{}' = 2n + m + k, k \in K$ be the segments that represent the start and end terminals of line k. The directed graph $G = (V, A)$ consists of the segments (are regarded as nodes) $V = N \cup \{\tau_1, \ldots, \tau_m\} \cup \{\tau_1{}', \ldots, \tau_m{}'\}$ and the arcs $A = V \times V$. For each line we have a subgraph $G_k = (V_k, A_k)$, where $V_k = N_k \cup \{\tau_k\}$

$\cup \{\tau_k'\}$ and $A_k = V_k \times V_k$. For each edge $(i, j) \in A$ we assign a distance $d_{ij} \geq 0$ and a travel time $t_{ij} \geq 0$. We assign a time window $[a_i, b_i]$ to each segment $i \in V$ for boarding and alighting. The time window indicates EBS lines can only take place between time a_i and b_i at each segment stop. For each node $i \in N$ we define l_i to be the number of passengers that should be loaded onto the line at the particular segment. We have that $l_i \geq 0$ for $i \in P$ and $l_i = -l_{i-n}$ for $i \in D$. Each line $k \in K$ has room for a certain amount of passengers, this capacity is given by C_k.

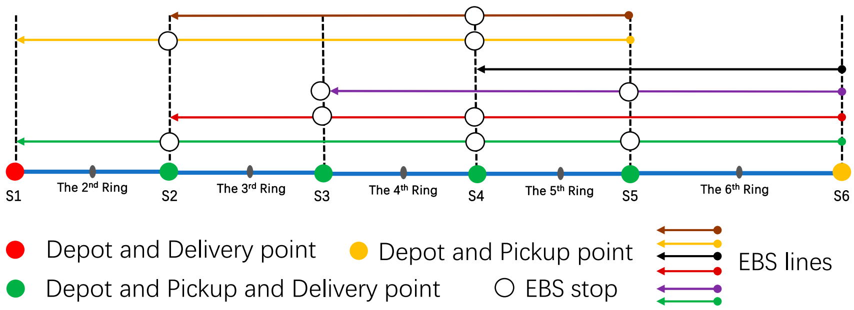

Figure 5. Schematic diagram of the EBS lines optimization results.

Each line k should follow a legal route from its start terminal τ_k to its destination terminal τ_k'. A legal route $\bar{r}$ is a simple (loop-free) path $\bar{r} = (\tau_k = v_1, v_2, \ldots, v_h = \tau_k')$ satisfying the time windows at the segments, the capacity of the line, and ensuring that a pickup takes place before a delivery, and that only requests serviceable by line k are carried out. More formally, we demand that the line only visits segments that can be serviced by the line, i.e., $v_i \in N_k$, $i = 2, \ldots, h-1$. A pickup-delivery pair should be served by the same line, and the pickup should take place before the delivery, hence we have $i \leq j$, $v_i \in P_k$, $v_j \in D_k$, $v_j = v_i + n$.

To ensure that time windows are satisfied, we introduce S_i to denote when the vehicle starts the service at segment v_i. We then have the constraints:

$$a_{v_i} \leq S_i \leq b_{v_i} \; i = 1, \ldots, h \tag{1}$$

$$S_i \geq S_i + t_{v_i, v_{i+1}} \; i = 1, \ldots, h-1 \tag{2}$$

$$a_{\tau_k} \leq S_1 \leq b_{\tau_k} \tag{3}$$

$$a_{\tau_k'} \leq S_h \leq b_{\tau_k'} \tag{4}$$

where $[a_{\tau_k}, b_{\tau_k}]$ is the time window of terminal τ_k and $[a_{\tau_k'}, b_{\tau_k'}]$ is the time window of terminal τ_k'. Finally, the capacity of the line should be respected throughout the path. For this purpose, we introduce L_i to denote the load of the line at segment i after serving segment i. Then we have:

$$L_i \leq C_k \; i = 1, \ldots, h \tag{5}$$

$$L_{i+1} = L_i + l_{i+1} \; i = 1, \ldots, h-1 \tag{6}$$

$$L_1 = 0 \tag{7}$$

$$L_h = 0 \tag{8}$$

The travel length of a given route $\bar{r}$ is

$$c_{\bar{r}} = \sum_{i=1}^{h-1} d_{v_i, v_{i+1}} \tag{9}$$

The whole problem can now be formulated as follows: let R be the set of all feasible routes. The boolean matrix ($\alpha_{j\bar{r}}$) for $\bar{r} \in R$ and $j = 1, \ldots, n$ is used to indicate whether request j is serviced using the route $\bar{r}$. The boolean matrix ($\beta_{k\bar{r}}$) for $\bar{r} \in R$ and $k = 1, \ldots, m$ is used to indicate whether the route $\bar{r}$ is carried out by line k. Using binary variables $x_{\bar{r}}$ to indicate whether the route $\bar{r}$ is used in the solution we get the following model:

$$\min f(x) = \sum_{\bar{r} \in R} c_{\bar{r}} x_{\bar{r}} \tag{10}$$

s.t.

$$\sum_{\bar{r} \in R} \alpha_{j\bar{r}} x_{\bar{r}} = 1 \; j = 1, \ldots, n \tag{11}$$

$$\sum_{\bar{r} \in R} \beta_{k\bar{r}} x_{\bar{r}} = 1 \; k = 1, \ldots, m \tag{12}$$

$$x_{\bar{r}} \in \{0, \; 1\} \tag{13}$$

Note that a dummy route is not assigned to any line, that is for any dummy route $\bar{r}$ we have that $\beta_{k\bar{r}} = 0, \forall \; k = 1, \ldots, m$.

We solved EBSLPPD by *VrpPd* software. *VrpPd* is software for solving capacitated vehicle routing problem with simultaneous pickup and delivery and time windows, it performs optimization using a specific algorithm (adaptive large neighborhood search with simulated annealing).

For general VRPPD problems, the pickup and delivery of each customer are generally less than the vehicle's capacity, yet the boarding volume of some segments of the commuting corridor is larger than the segment capacity of the EBS line. At this time, the algorithm for VRPPD be not capable to solve this problem, so it is necessary to decompose the OD distribution between segments which exceeds the segment capacity of the EBS line. Figure 6 demonstrates the splitting result from the original OD distribution to the new one. In our subsequent analysis, we assume that the capacity of the line is 2000, 3000 or 4000 passengers/h, so the passenger flow distribution between segments is split by a multiple of 1000. The travel distribution of 3500 between S5 and S3 is divided into four travel distributions: three 1000 and one 500. The travel distribution of 1500 between S5 and S4 is also divided into one 1000 and one 500. The distribution between all segments is split and input into requests (or orders) of *VrpPd* software. In this research, the optimization problem of EBS does not set up the fixed terminals, the starting and ending terminals of the EBS line need to be optimized simultaneously. Therefore, the EBSVRPPD problem belongs to Multi-depot problems. The time window is set to 120 min during the morning rush hour, during which passengers are transported from the starting terminals to the destination terminals. In the *VrpPd* software setup, the optimization goal is to minimize the total route length for all lines of EBS.

To apply the algorithm to wider practical uses, the main design procedure for EBS route planning are as follows:

Step 1: Specify the OD distribution by travel-demand analysis of MPL data or other methods.

Step 2: Subsample OD demand of long-distance commuters, the threshold value of long-distance is determined based on the speed of cars, the express bus speed and last-mile travel time in the local corridor.

Step 3: Decompose the OD distribution between two segments which exceeds the segment capacity of the EBS line.

Step 4: Define on a graph where $P = \{1, \ldots, n\}$ is the set of pickup segments, and $D = \{n + 1, \ldots, 2n\}$ is the set of delivery segments. Request i is represented by segment i and $i + n$. $K = \{1, \ldots, m\}$ is the set of all EBS lines.

Step 5: Assign a time window $[a_i, b_i]$ to each segment $i \in V$ for boarding and alighting.

Step 6: Input $P = \{1, \ldots, n\}$, $D = \{n + 1, \ldots, 2n\}$, Request i, the time window $[a_i, b_i]$, segment capacity C_k.

Step 7: Solve EBSLPPD by running *VrpPd* software and output optimal routes result: the number of lines; start terminal, stops and destination terminal of every EBS line; total operation mileage; passengers on/off at stops.

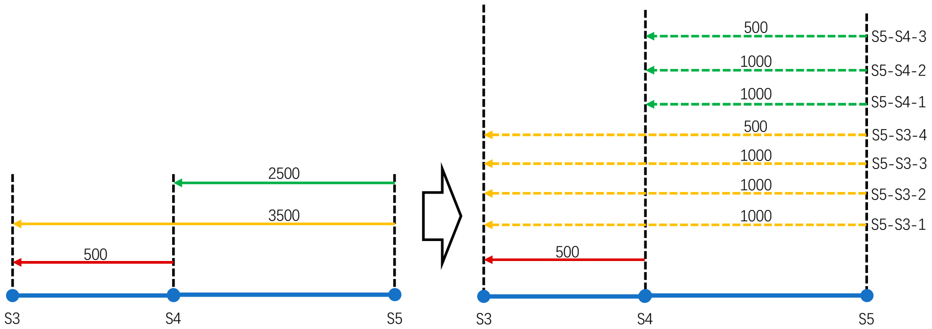

Figure 6. Schematic map of trip distribution splitting between segments (units: passengers/h).

4. Result and Discussion

The mathematics' model and solution algorithm for EBS route optimization offer a better way to improve the transit operation efficiency for a corridor with huge travel demand. The problem and the mathematical model proposed in this paper is interesting and meaningful from four aspects: (i) integrating route planning into limit-stop scheduling; (ii) taking into account segment capacity as a constraint; (iii) considering multiple depots to optimize EBS routes; and (iv) decomposing the OD distribution between segments which exceeds the segment capacity of the EBS line.

We conducted sensitivity analyses to examine the results of operation statistics under different scenarios such as different vehicle capacity, route segment capacity, and headways. We compared the total number of lines, route length, fleet size, and total operating length. We have set three different EBS segment capacity: 2000, 3000 and 4000 (passengers/h). The optimized route results are shown in Figures 7–9 respectively. The OD distribution with the same color and line type is transported by the same EBS line. The line that only bears one OD distribution is a nonstop EBS line. The line that bears multiple OD distribution sets a stop at the end segment of each OD distribution.

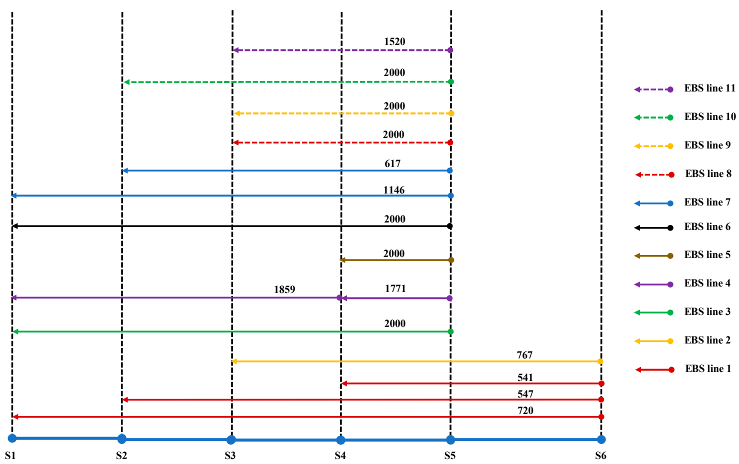

Figure 7. Optimization result and OD distribution transported by EBS lines (units: passengers/h, segment capacity = 2000 passengers/h).

We obtained the number of lines and routes length (km) of EBS under different scenarios via *VrpPd*, Other operation parameters are also calculated indirectly (shown in Table 2). The results suggest that using larger vehicles, larger segment capacity, and shorter headways can achieve fewer EBS lines and reduce the total operation length, which would control operation costs when the route segment capacity is changed from 2000 to 3000 passengers/h. the scenario with the segment capacity of 4000 passengers/h has a minimum of number and length of lines with the increasing of the fleet size and the total operation length.

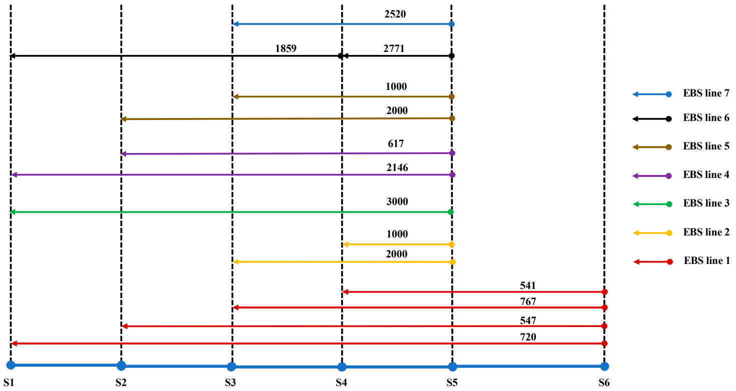

Figure 8. Optimization result and OD distribution transported by EBS lines (units: passengers/h, segment capacity = 3000 passengers/h).

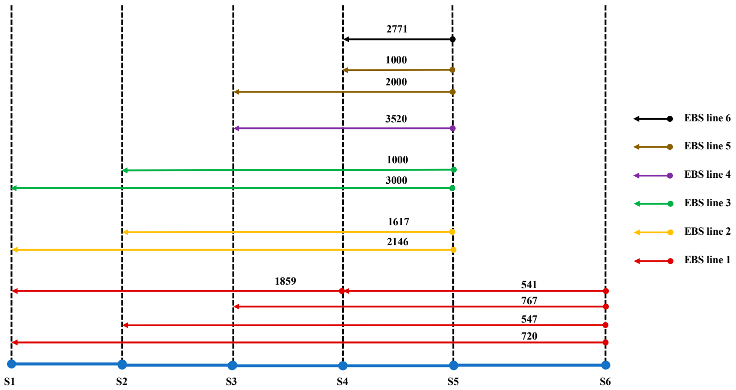

Figure 9. Optimization result and OD distribution transported by EBS lines (units: passengers/h, segment capacity = 4000 passengers/h).

Table 2. The EBS operation statistics comparison between different scenarios.

Scenario Number	Vehicle Capacity	Route Segment Capacity (passengers/h)	Headway (min)	The Number of Lines	Route Length (km)	Fleet Size	Total Operation Mileage (km)
1		2000	3	11	204	220	4080
2	100	3000	2	7	133	210	3990
3		4000	1.5	6	109	240	4360
4		2000	4.5	11	204	154	2856
5	150	3000	3	7	133	140	2660
6		4000	2	6	109	180	3270

For these scenarios with the same segment capacity (such as scenarios: 1, 2 and 3 with vehicle capacity 100; or scenarios: 4, 5 and 6 with vehicle capacity 150 passengers/h), their operation statistics results show that the number of lines and route length are the same. For the different vehicle capacity (100 or 150 passengers/h), these scenarios with the same segment capacity (scenarios 1 and 4, scenarios 2 and 5 or scenarios 3 and 6) result in the different fleet sizes and total operation mileage. When the route segment capacity is 2000, 3000 and 4000 passengers/h respectively, within the scenario with the vehicle capacity 150 passengers/h, the fleet size and total operation mileage decreased by 30%, 33% and

25% respectively from the vehicle capacity 100 passengers/h. This showed that the increase of vehicle capacity can effectively reduce the fleet size and total operation mileage, but the larger the segment capacity, the smaller the decreased range the fleet size and total operation mileage.

For these scenarios with the same vehicle capacity (scenarios: 1, 2 and 3; or scenarios: 4, 5 and 6), their operation statistics results showed obvious differences. When the vehicle capacity is 100 passengers/h, within the scenario with the segment capacity 3000 passengers/h, the number of lines is reduced by 36% from the segment capacity 2000 passengers/h, the route length is reduced by 35%, the fleet scale is reduced by 5%, and the total operation mileage is reduced by 2%; within the scenario with the segment capacity 4000 passengers/h, the number of lines is reduced by 14% from the segment capacity 2000 passengers/h, the route length is reduced by 18%, the fleet scale is increased by 14%, and the total operation mileage is increased by 9%. When the vehicle capacity is 150 passengers/h, within the scenario with the segment capacity 3000 passengers/h, the number of lines is reduced by 36% from the segment capacity 2000 passengers/h, the route length is reduced by 35%, the fleet scale is reduced by 9%, and the total operation mileage is reduced by 6%; within the scenario with the segment capacity 4000 passengers/h, the number of lines is reduced by 14% from the segment capacity 2000 passengers/h, the route length is reduced by 18%, the fleet scale is increased by 18%, and the total operation mileage is increased by 22%. This shows that the increase of segment capacity may increase the total operation mileage when the vehicle capacity is fixed. The main reason is that the decreased departure interval increases fleet size and operation mileage.

So, we recommend that the transit agency adopt 150-passenger vehicles, choose 3000 passengers per hour as the route segment capacity, and set three minutes for the headway, because this scenario results in minimum fleet size and minimum total operation length. To obtain these conditions, the transit operator might invest in infrastructure such as purchasing larger vehicles, building exclusive EBS lanes, and installing a transit signal priority system, which may increase capital costs. Agencies need to balance their operation and capital costs based on specific cost–benefit analyses.

5. Conclusions

This paper established a systematic method to design EBS routes with limited-stop service for long-distance commuters. We suggest that MPL data are analyzed to determine the OD distribution of commuting trips. The evidence of OD estimation based on the mobile phone data help us precisely decide the number of potential passengers of the EBS. Optimal EBS routes provide passengers with services similar to customized public transport. Passengers take EBS bus vehicles on the designated stops to quickly arrive at the destination zone. We put forward the improved optimization algorithm for the design of EBS routes with the segment capacity constraint to determine start stations, end stations and the stops of EBS lines. In order to apply the optimization algorithm, it is necessary to decompose the OD distribution between segments which exceeds the segment capacity of the EBS line. Considering that there are bus terminals and stations between the ring roads along the corridor, we can treat all sections as depots input to optimize the start or ending station, which will be very helpful to reduce the length of the line.

Based on sensitivity analyses, which was done using data for the Changping Corridor (Beijing, China), several significant conclusions can be drawn:

(1) Using larger vehicles, larger segment capacity and shorter headways can achieve fewer EBS lines and reduce the total operation length, which would control operation costs when the route segment capacity is changed from 2000 to 3000 passengers/h. Although the scenario with a segment capacity of 4000 passengers/ h has the minimum number and line length, the fleet size and total operating mileage are increased compared with other scenarios with the segment capacity 2000 or 3000 passengers/h.
(2) The increase of vehicle capacity can effectively reduce the fleet size and total operation mileage, but the larger the segment capacity, the smaller the decreased range of the fleet size and total operation mileage.

(3) The increase of segment capacity may increase the total operation mileage when segment capacity is more than 3000 passengers/h.

There are some limitations in this study. For future studies and practice, researchers and practitioners should pay attention to several important issues:

(1) The performance of the proposed routes has not been examined. Therefore, a program evaluation analysis is necessary for the future.
(2) Minimizing both the passenger and operator costs as the optimization objective should be explored in future studies.

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