BUS ROUTE DESIGN WITH LIMITED TRAVEL TIME

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Abstract. Routing problems are especially important for public transport and especially for urban transport. This research deals with designing a bus route to satisfy the demands of most passengers within a limited total bus travel time. A Simulated Annealing (SA) algorithm is proposed for optimizing the routing design. Before applying the proposed SA algorithm, the Taguchi method is adopted for optimizing the setting of parameters. The experimental results show that the proposed SA algorithm with the optimal parameters setting results in better routes than those designed by other research methods.

Keywords: bus route design, simulated annealing, transportation, Taguchi method.

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Introduction

The design of public transportation has become increasingly important for prosperous cities. A well designed public transport network can influence passengers to go to their destinations by public transport, such as shuttle bus, subway and so on, rather than in private cars. Therefore well designed public transportation can solve the problems of traffic congestion and a shortage of parking spaces. Good public transport may even increase the number of sightseers due to the convenience of transport and thus bring more economic benefits.

In general, every city has a traffic centre which contains the railway station, the subway station and/or the high-speed train station. For a passenger who lives outside the city and wants to go to somewhere in the city, the general way is taking a high-speed train to reach the traffic centre of the city, and then transfer to a shuttle bus or subway to go to their destination. If the transfer is convenient and speedy, then the inclination of people to enter or leave the city by public transport can be increased. However if the passenger's destinations or starting points in the city cannot be reached by public transport, then passengers will prefer to drive their private cars.

Zhao and Zeng (2006) mention that there are three key objectives of good public transport systems. The first is that the passengers can reach their destinations in the shortest time. The second is that the public transport system covers the whole region, to enable all passengers to reach their destinations through the transport system. The third is that the number of transfers for passengers should be minimized, to avoid unnecessary waste of time. This research focuses on the second objective to propose a method for designing a network of bus routes to maximize the number of passengers to be serviced.

The present research is unlike the research by Chakroborty and Wivedi (2002), Zhao and Zeng (2006) and others, who start with the O–D matrix and aim to minimize the average number of transfers and total travel time. This research deals with designing bus routes for an area where the travel time and potential demand along all main streets are given. Due to the expense of service, the designed bus route cannot pass through all main streets in the given area. Therefore, the goal is to maximize the servicing of total demand within a limited cost (total travel time). Peško (2003) proposes a model to find the route in an urban area with given flows of passengers. The goal is the maximal total time saving of passengers using the line, and the route has to pass through all demand points.

The problem addressed in this paper is related to that introduced in the papers by Jerby and Ceder (2006)

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and Kuo and Luo (2011). They propose a heuristic to find a route passing through some main streets in such a way that it satisfies the maximum demand, and this approach is adopted here. However, the heuristic proposed by Jerby and Ceder (2006) is a local search algorithm and Kuo and Luo (2011) did not deal with the setting of optimal parameters. Consequently, there is still an opportunity to improve on their bus route solutions.

1. Proposed Methodology

In this study, the Simulated Annealing (SA) algorithm is adopted to find the optimal bus route. Kirkpatrick *et al.* (1983) first proposed the SA method to solve problems. To date, the SA method has been widely applied in many complex problems (Lee *et al.* 2007), and even successfully in problems of route planning (Osman 1993; Van Breedam 1995; Chiang, Russell 1996; Bent, Van Hentenryck 2004; Tavakkoli-Moghaddam *et al.* 2006).

SA searches randomly for new neighbourhood solutions. If the new neighbourhood solution has better performance than the current solution, then the new neighbourhood solution will replace the current solution and the search for new solutions will continue. This process of searching neighbourhood solutions is called a 'move'. However, if the performance of the neighbourhood solution is worse, there is still a chance for the solution to replace the current solution to avoid the problem of being locked into a local optimum (Jahangiri *et al.* 2011). The worse solution will be accepted with a probability $e^{(-\Delta Z/U)}$, which depends on two parameters U and ΔZ. U is the temperature, which gradually declines during the searching process. $-\Delta Z$ is the degree of improvement for the new solution (X') compared with the current solution (X). If $Z(X')$ and $Z(X)$ are the performance for (X') and (X), and if a lower value indicates better performance, then $\Delta Z = Z(X') - Z(X)$. In the beginning of the search, the temperature is higher (the value of U is larger), and the probability of accepting a new solution is also higher. However, the temperature will gradually decline (the value of U become smaller) during the search process, and the probability of accepting new solutions will become smaller. In addition, if ΔZ is large (compared with the current solution, the performance of the neighbourhood solution is poor), the probability of accepting the neighbourhood solution will be smaller. The SA flowchart is illustrated in Fig. 1.

It can be seen from this brief account that the generation of an initial solution, the moves and the cooling process are important operations in the SA optimization process. Kuo and Luo (2011) proposed an SA-based circular route optimization procedure for the bus route design problem. Their proposed procedure includes these operations. However, they did not deal with the setting of parameters of the SA procedure. This research will adopt the operations proposed by Kuo and Luo (2011), with optimal parameter setting, to find the bus route. The details of these important operations which are described in the sections that follow are based on Kuo and Luo (2011).
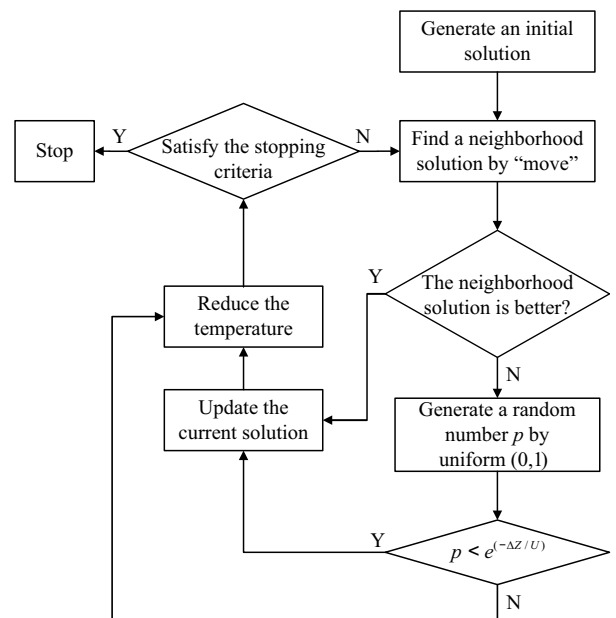

Fig. 1. SA flowchart

1.1. Initial Solution Generation

Suppose that i and j are two adjacent nodes in the network, d_{ij} is the passenger demand of the link between node i and node j, t_{ij} is the travel time of the bus in the link between node i and node j. The average interval time that passengers get into buses, c_{ij}, can be calculated as t_{ij}/d_{ij} when the bus travels in the link between node i and node j. If c_{ij} of a link is smaller, it indicates that the bus can serve more passengers in a shorter time. In order to plan a route that allows the bus to serve more passengers in the same travel time, the links with smaller c_{ij} should be selected in preference to others as sections of the bus route. In this study, c_{ij} is considered the basis for generating initial solutions, and the generating steps are as follows:

Step 1: Suppose that Node 1 is the traffic centre. Find the minimum total for c_{ij} for routes between Node 1 and all other nodes in the network, using Floyd's minimum path algorithm (Teodorovic 1986).

Step 2: For all the routes found in Step 1, find a route with the maximum total c_{ij}, and denote the total c_{ij} of the route be *TC*.

Step 3: For all the routes found in Step 1, find all the routes with the total c_{ij} between $\alpha \cdot TC$ and $\beta \cdot TC$, where α and β are determined by the user and $0 \leq \alpha \leq \beta \leq 1$.

Step 4: Randomly select one of the routes found in Step 3 as the initial solution.

The values of α and β will determine the length of the initial path. Suppose that the values of α and β are set to be smaller, a shorter initial path will be generated and vice versa.

1.2. Move

A move is an operation in SA to find a neighbourhood solution that can be reached from the current solution.

This research proposes a delete-replace approach for finding the neighbourhood solution. The move operation contains two parts. The first part deletes a section in the whole bus route. The second part generates a new path between the nodes selected in the first part to replace the deleted path. By using the move operation, a new circular-type route can be found. The detail of the delete-replace approach is as follows:

Part 1: Deletion

Step 1: Combine consecutive h links to generated $m - h + 1$ sections (supposing that a bus route contains m links) and then calculate the average interval time, c_q, for section q.

Step 2: Randomly select one of the sections developed in Step 1 by the probability, $f_q = c_q \Big/ \sum_1^{m-h+1} c_q$.

Step 3: Delete the section selected in Step 2.

Part 2: Replacement

Step 4: Randomly select a node not on the current bus route.

Step 5: If the section deleted in Step 3 is between node i and j, Floyd's minimum path algorithm (Teodorovic 1986) is used to find the path between the node selected in Step 4 and the two nodes node i and j.

Step 6: The paths found in Step 5 replace the path deleted in Step 3.

Step 7: Stop.

By using the above steps, a new bus route can be found, which has a total c_{ij} that is smaller than the original value. However, it is possible that a link might be served twice in the route plan. It is not reasonable to add the potential demand of the link twice. To overcome this difficulty, a modified deletion method is adopted by changing Step 1 and Step 2 as follow:

Step 1: Identify all repeated links in the current route as sections.

Step 2: Random select one of the sections identified in Step 1.

This deletion method is called Deletion 2, while the previously proposed method is called Deletion 1. The two deletion methods are used alternately during the solving process. Deletion 1 is used first, Deletion 2 is used after G iterations, and Deletion 1 is again used after another G iterations. In this way, the deletion methods are used alternately until the stopping criterion (maximal number of iterations) is satisfied.

1.3. Cooling Process

During the SA optimization process, if a new solution X', which is not better than the current solution X, is found, the probability of accepting the new solution will be $e^{(-\Delta Z/U)}$. ΔZ is $Z(X') - Z(X)$, and U is a parameter called temperature. The temperature will gradually decline (the value of U becomes smaller) during the search process to decrease the probability that new solutions will be accepted. The process of reducing the temperature is called cooling.

This study adopts the cooling function which was first introduced by Lundy and Mees (1986), which outperforms the commonly used geometric cooling function (Lee *et al.* 2007). The temperature is cooled according to equation (2):

$$U_{a+1} = \frac{U_a}{1 + \beta \cdot U_a}, \quad a = 1, \ldots, A - 1, \tag{2}$$

where: U_a is the temperature in iteration a; A is the total number of search iterations for SA; β is the rate parameter which can be calculated by equation (3):

$$\beta = \frac{U - U_A}{(A - 1) \cdot U \cdot U_A}, \tag{3}$$

where: U is the initial temperature and U_A is the final temperature.

The proposed SA model involves the temperature being reduced each iteration. This is different from general SA where a certain number of iterations takes place between each cooling.

2. Empirical Illustration

The proposed SA algorithm was validated on the problem which was first proposed by Jerby and Ceder (2006) and was subsequently tested by Kuo and Luo (2011). In Jerby and Ceder (2006) one main problem and several smaller problems were proposed. Because they only provided the complete data for the main problem, the present study can only be fully tested against their main problem. If the proposed algorithm has good performance on the larger problem, then it is assumed that it can solve the smaller problem successfully.

The routing plan results of Jerby and Ceder (2006) and Kuo and Luo (2011) are shown in Figs 2 and 3 respectively. In Fig. 2, the first number in each link is the travel time and the second number is the passenger demand, and the upper limit for the total travel time of the route is 100. The total travel time of the route planned through the heuristic algorithm proposed by Jerby and Ceder (2006) is 100, and the passenger demand serviced is 142.2. There is repetition between Node 12 and Node 16, and between Node 13 and Node 17, in the planned route in Fig. 2. Jerby and Ceder (2006) assume that the passenger demand of repeated links will be 20% of the original. Thus, the demand for passenger service over the two sections is 2.4 ($2 + 0.2 \cdot 2$) and 10.8 ($9 + 0.2 \cdot 9$) respectively.

Fig. 3 illustrates the routing plan results of Kuo and Luo (2011). The total travel time of the route is 95 and the passenger demand serviced is 150.4. There is repetition between Node 13 and Node 17, and between Node 20 and Node 25, in the planned route in Fig. 3. The routing plan identified by Kuo and Luo (2011) is better than the one found by Jerby and Ceder (2006).

In applying the proposed SA algorithm, many parameters must be defined by the user. After several tests, it has been found that changing these parameters can influence the performance of the proposed method. In this research, the Taguchi method is adopted for optimizing parameters. The Taguchi method has been successfully applied as a systematic approach for optimization (Phadke 1989). The Taguchi method uses an orthogonal
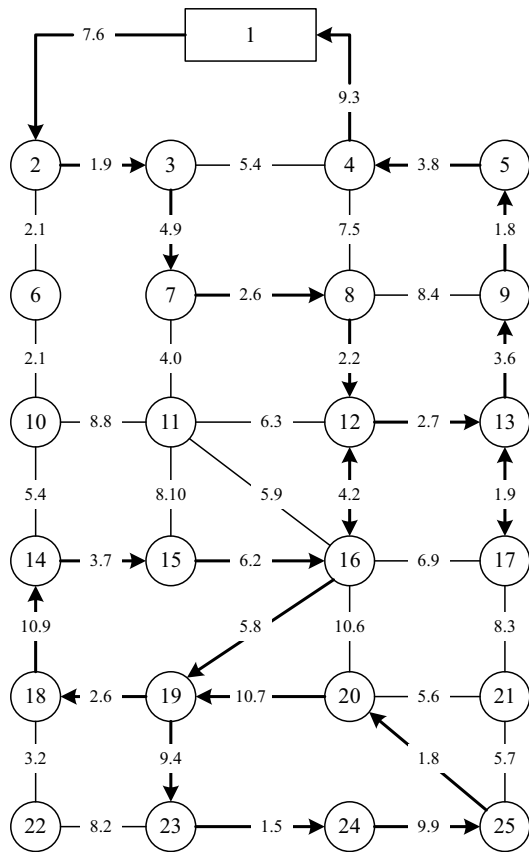
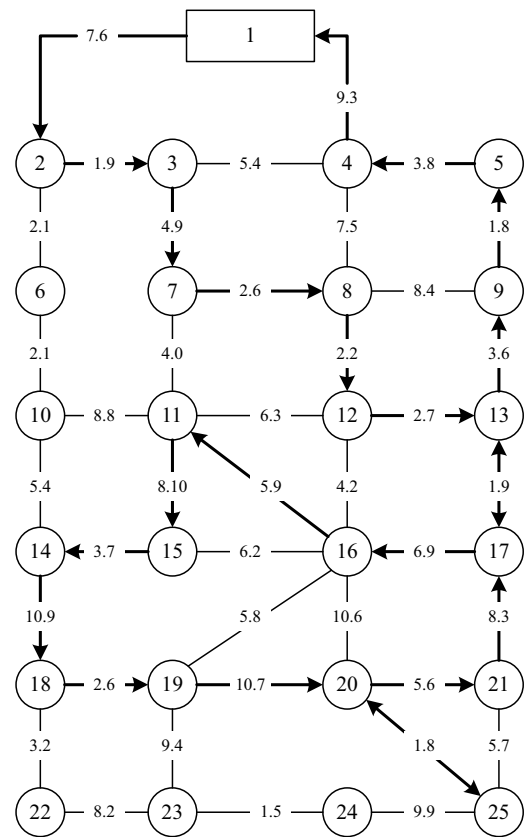**Fig. 2.** The routing plan results of Jerby and Ceder (2006)

Fig. 3. The routing plan results of Kuo and Luo (2011)

array to organize the experimental results. If there is no interaction between factors, the effect of every factor can be calculated and the optimal combination of parameters found (Kuo *et al.* 2008). The summary of experimental levels is given in Table 1.

Table 1 shows that there are five four-level factors in the present study. The five factors are denoted A, B, C, D, and E. For factor A, α and β are combined into one factor. Moreover, according to the test results, optimal values are convergent when the number of iterations is more than 500 and it takes less than one second to find the optimal solution when the maximum number of iterations is set as 10000. Therefore, the maximum iteration is fixed as 10000.

An $L_{16}(4^5)$ orthogonal array was used to collect the experimental data. In the $L_{16}(4^5)$ orthogonal array, there are 16 treatments. For each treatment, the proposed optimization method is run ten times and the best result will be the performance of the corresponding treatment. The results are shown in Table 2.

By using the additive property, the average responses by factor levels can be found. The associated factor effect plots are shown in Fig. 4.

Because the performance in the present study is the larger the better, Fig. 4 shows that the optimal combination of factor level is $A_3B_3C_3D_4E_2$. That means that the optimal parameters are set to α = 0.7, β = 0.8, e = 5, G = 25, U = 8 and U_e= 2. This parameter setting is then adopted for finding the optimal routing plan. The routing plan obtained by the proposed method is shown in Fig. 5. The total travel time is 99, and the demand for passenger service is 154.4.

Table 1. The experimental levels of parameters setting

Factor	Description	Levels of factor			
		1	2	3	4
A	The lower and upper limit of the total c_{ij} when the initial solution is generated (α – β)	0.9–0.1	0.8–0.9	0.7–0.8	0.6–0.7
B	The quantity of combined links in Deletion 1 (*e*)	1	3	5	7
C	The interval iteration value during the change from Deletion 1 (or Deletion 2) into Deletion 2 (or Deletion 1) during the searching process (*G*)	5	15	25	35
D	The initial temperature of SA (*U*)	5	6	7	8
E	The final temperature of SA (*U*_e)	1	2	3	4

Table 2. $L_{16}(4^5)$ orthogonal array and experimental results

Treatment	$L_{16}(4^5)$					Performance
	A	B	C	D	E	
1	1	1	1	1	1	108.0
2	1	2	2	2	2	143.2
3	1	3	3	3	3	149.0
4	1	4	4	4	4	148.0
5	2	1	2	2	4	131.4
6	2	2	1	4	3	145.4
7	2	3	4	1	2	151.0
8	2	4	3	2	1	147.2
9	3	1	3	4	2	138.0
10	3	2	4	3	1	141.0
11	3	3	1	2	4	146.6
12	3	4	2	1	3	153.8
13	4	1	4	2	3	121.2
14	4	2	3	1	4	147.0
15	4	3	2	4	1	152.0
16	4	4	1	3	2	149.0

Fig. 4. The effect of factor levels

Fig. 5. The routing plan results of the proposed SA algorithm

lected from the integers 1 to 10. The solutions are shown in Table 3, where Network 1 is the problem proposed by Jerby and Ceder (2006), and Networks 2 to 8 are the problems proposed by Kuo and Luo (2011).

As shown in Table 3, the proposed SA algorithm has an average improvement of 8.58% and 2.00% as compared with the heuristic algorithm proposed by Jerby and Ceder (2006) and Kuo and Luo (2011) respectively. Moreover, the proposed SA algorithm produces the best route design for all network cases. The method finds only a small improvement for some network cases, such as Networks 6 and 8, and in the case of Network 4 finds no improvement at all.
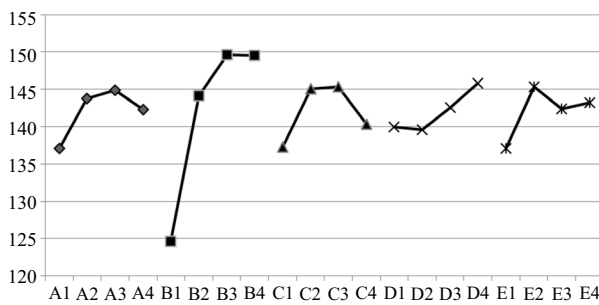
Based on the problem proposed by Jerby and Ceder (2006), Kuo and Luo (2011) followed the same structure to generate seven problems. The relevant positions of all nodes are the same. The links between each node and the adjacent nodes are randomly generated, and there are 40 links in all. In addition, the demand for passenger service in each link and the travel time are randomly se-
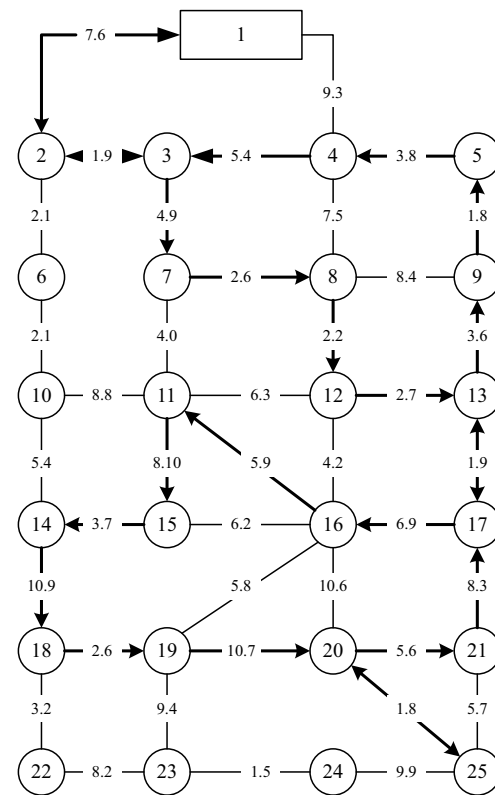
Table 3. The experimental results

Network number	Performance of methods					
	Jerby and Ceder (2006)		Kuo and Luo (2011)		Proposed SA algorithm	
	Total demand	Improvement by proposed procedure	Total demand	Improvement by proposed procedure	Total demand	
1	142.20	8.58%	150.40	2.66%	154.4	
2	–	–	135.00	2.67%	138.6	
3	–	–	148.80	3.76%	154.4	
4	–	–	162.60	0.00%	162.6	
5	–	–	144.60	4.15%	150.6	
6	–	–	146.60	0.68%	147.6	
7	–	–	161.40	1.73%	164.2	
8	–	–	126.80	0.32%	127.2	
Average	142.20	8.58%	147.03	2.00%	149.45	

Conclusion and Discussion

In this research, an Simulated Annealing (SA) algorithm is proposed for designing the bus route to maximize the quantity of passengers who can be serviced by buses within the same travel time limit. In the propose SA algorithm, there are seven parameters which can influence the performance of the optimization results. The Taguchi method is adopted for optimizing these parameters. The experimental results show that the proposed SA algorithm with optimal parameter setting can find better bus routes than other algorithms.

The problems solved in this study were designed for only a single bus route. Therefore the proposed method can also solve the bus route design problem in rural areas, because in that case the number of bus routes is relatively small. However, based on the ideal of population service, in some cases in which a few people live far away from their neighbours the bus route should be adjusted. In the case of a metropolitan city, many bus routes are required to satisfy passengers demand. Therefore, planning several bus routes simultaneously would be necessary to enable the public transport system to provide better service over a larger range, which is the direction that this research should take in the future.

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