Characteristic of Passenger’s Route Selection and Generation of Public Transport Network

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Abstract: Scheduled liner service is a proper system for mass transportation and it is employed by wide range of transportation modes, such as railway, airline, maritime container shipping and bus. To get more customers, providers of the liner services are required to organize effective routes and networks of the service incorporating the characteristic of the passenger’s route selection. This paper tackles to the problem of generating Public Transit Network as one of scheduled liner service. The method generating PTN is based on Multi Agent System that incorporates the characteristic of passenger’s route selection. And it is also reported that the developed method successfully output best solution for a benchmark problem.

Key Words: multi agent system, public transportation network, optimization.

1. Introduction

Scheduled liner service is a proper system for mass transportation and it is employed by wide range of transportation modes, such as railway, airline, maritime container shipping and bus. Service providers open their schedule (i.e. route path and time table) to service users and service users select their proper route. Thus, service providers are required to organize effective transport network considering characteristic of user’s route selection.

This paper focuses on public transport network (Hereinafter called PTN) for bus as scheduled liner service. Generating PTN is a hard problem. Since the problem includes many variables such as vehicle number, transit route, line number, classical method like mathematical programming faces many difficulties in the process of mathematical formulation and optimization. Furthermore it easily leads to combinatorial explosion even though the number of station or bus stop is small. Most of previous studies attacking the problem rely on heuristic or meta-heuristic method. However heuristics does not have flexibility to modify or improve program codes.

The authors propose Multi Agent System (hereinafter called MAS) as an algorithm generating PTN. One agent represents one line composing PTN (Hereinafter called Line Agent) and it competes for passengers by evolving with changing route. Final solution as PTN is a set of line agents survived after evolution process.

One of advantage to employ MAS is flexibility to modify evolution rules to match with problems given. In this paper, evolution rule of line agents is modified to incorporate characteristic of user’s route selection.

This paper is organized as follows.

Section 2 clarifies the characteristic of user’s route selection. Problem of generating PTN is defined in Section 3. Section 4 explains a method with MAS generating PTN. The analysis results are presented in Section 5. Finally, Section 6 gives conclusion.

2. Route Selection

In this section, characteristic of passenger’s route selection is made clear by analyzing a census data for railway and subway in Japan.

2.1 Measure

Latora [1] presented an index to measure the effectiveness of PTN. The index is named to “Efficiency” and is applied to railway networks in Japan. The following equations define the efficiency, $E_{glob}$.

$$E_{glob} = E(\Gamma)/E(\Gamma_0)$$ (1)

$$E(\Gamma) = \sum_{i \neq j} 1/d_{ij}$$ (2)

where, $\Gamma$ is a target network, $i, j$ are nodes representing station belonging to $\Gamma$, $d_{ij}$ is network distance between $i, j$. $\Gamma_0$ is the idealized target network meaning that any two nodes in $\Gamma$ are connected by a straight link whose distance is $d_{ij}$. The definition implies that $E_{glob}$ is ranging between 0 and 1 and $E_{glob} = 1$ means target network matches with idealized network.

Furthermore, taking into account of the effect of demand, The authors introduce new index $ED_{glob}$ as demand weighted efficiency [2].

$$ED_{glob} = ED(\Gamma)/ED(\Gamma_0)$$ (3)

$$ED(\Gamma) = \sum_{i \neq j} D_{ij}/d_{ij}$$ (4)
where, \( D_{ij} \) is demand from station \( i \) to \( j \).

### 2.2 Route Selection Algorithm

Table 1 summarizes the analysis result. In the table, the efficiency, \( E_{\text{glob}} \), and the demand weighted efficiency, \( ED_{\text{glob}} \), are computed for subway networks in Nagoya, Osaka, Tokyo, one railway network in Kanto area (East Japan Railway company, referred as JR) and combination of railway and subway networks in Tokyo. The column “Demand” describes average data per day obtained from [3]. The demand weighted efficiency \( ED_{\text{glob}} \) is larger than the simple efficiency \( E_{\text{glob}} \) for all networks. It implies that the demand of PTN service becomes larger between two stations with higher efficiency. Thus, this qualitative phenomenon is imperative for considering algorithms generating effective PTN.

<table>
<thead>
<tr>
<th>Network</th>
<th>Station Num.</th>
<th>Demand (per day)</th>
<th>( E_{\text{glob}} )</th>
<th>( ED_{\text{glob}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nagoya</td>
<td>76</td>
<td>139,815</td>
<td>0.782</td>
<td>0.844</td>
</tr>
<tr>
<td>Osaka</td>
<td>99</td>
<td>172,072</td>
<td>0.732</td>
<td>0.857</td>
</tr>
<tr>
<td>Tokyo</td>
<td>198</td>
<td>496,787</td>
<td>0.658</td>
<td>0.895</td>
</tr>
<tr>
<td>JR</td>
<td>458</td>
<td>2,477,228</td>
<td>0.765</td>
<td>0.900</td>
</tr>
<tr>
<td>JR+Tokyo</td>
<td>622</td>
<td>3,538,629</td>
<td>0.739</td>
<td>0.894</td>
</tr>
</tbody>
</table>

Although \( E_{\text{glob}} \) and \( ED_{\text{glob}} \) are computed with the all stations in the target network, it becomes just “direct distance” \( / \) “network distance” applying to specific two stations and the authors call this index as “single efficiency”.

Figure 1 shows the distributions of the single efficiencies and the demand in various types of distinctive networks, the directly connected line (Tozai Line), the largely deformed line (Marunouchi Line), the circular line (Yamanote-Line) and the combination network JR and subway in Tokyo. The left column of the figure shows the target network composed of stations and railway. The middle column is probability distribution of the single efficiency based on the frequency of OD pair (pair of origin and destination station). The frequency is normalized by number of all pairs of two stations to be a probability. The third column is probability distribution of the single efficiencies based on the demands between origin and destination stations. The demand is normalized by the total demand to be a probability.

Figure 1 shows that the demand among the low single efficiencies become small for all networks, and about 80% of the demand concentrate on the station pairs whose single efficiency is more than 80%.

This phenomenon of route selection tendency is reflected in the evolution rule of line agent explained in Section 4. More specifically, changing line route involving inefficient detour is associated with reduction of passengers using the line. It means incorporating the possibility to deteriorate the profit of the line.

### 3. Problem Definition

As a matter of convenience, a transportation mode is set to bus line network in this paper. Thus, vehicle is bus, physical infrastructure network is street and bus stops. All of the information on street network, position of bus stops, demand matrix whose element is demand between two bus stops, vehicle speed and seating capacity are given. The demand matrix is often referred to as an OD (Origin, Destination) matrix.

![Fig. 1 Probability of single efficiency based on number of OD pair (middle column) and on demand (right column).](image)

Solution is a set of bus line that has information about route and vehicle number. The route of bus line is defined by a set of consecutive links connecting bus stops and it is assumed that the vehicle travels back and forth in the route of assigned line. Furthermore, since express bus is not considered, vehicles stop at all bus stops on its route. Figure 2 shows an example of problem and solution.

![Fig. 2 Problem definition and example of solution.](image)

The line agent in Section 4 competes for passengers changing its transit route and number of vehicle, interacting with another agent and solution as PTN is a set of line agents finally survived after the evolution process. The evaluation function similar to the following equation is applied frequently to the problem of PTN [4]. In this paper, the same evaluation function is employed.

\[
\min Z = \sum_{S, S' \in ST} T_{S_5, S_5} D_{S_5, S_5} + \sum_{k \in BL} B_{k_4}
\]

where, \( \min Z \) means target is minimizing the value \( Z \), \( ST \) is a set of bus stops, \( BL \) is a set of bus lines, \( D_{S_5, S_5} \), \( T_{S_5, S_5} \) are demand and traveling times from the bus stop \( S_5 \) to \( S_5 \) respec-
tively. The traveling time is composed of not only in-vehicle time, but also expected waiting time. $B_{Lk}$ is a number of vehicles deployed into the bus line $L_k$. The traveling time from the bus stop $S_i$ to $S_j$, is simply calculated by Euclidean distance on street network and service speed of vehicle.

The first term in Eq. (5) is user’s cost and the second term is service provider’s cost. $w_1$ is control parameter, small $w_1$ reduces traveling time as user’s cost and large $w_1$ reduces number of bus as company’s cost. Passengers hope to reduce the first term and transportation companies hope to reduce the second term. Generally speaking, relationship between two terms is trade-off relationship and it is one reason of the difficulties to solve the PTN generation problem. One extreme condition is connecting all pairs of bus stops by direct shuttle service. Although it is extremely convenience for passengers, it requires an enormous cost to transportation companies.

4. Multi Agent System

The developed MAS separates several components as follows.

- Generating initial set of line agent
- Route selection of passengers
- Evolution of line agent

The explanation of the first component, generation of initial set of line agent, is omitted in this paper due to space limitation and out of the scope of this paper. Briefly speaking, a network generation model was modified to generate initial line agents. The network evolution models are investigated actively in the research field of complex network and a paper [5] reported that a model generates physical infrastructure network of a subway successfully. The detailed characteristic and application of our method is reported in [6]. In addition, it is recognized that the initial set of line agent affects to the transportation performance of obtained PTN and computing times [7].

Evolution process starts after the generation of initial set of line agents. Figure 3 illustrates the flow diagram of the process. # 2 in Fig. 3 (Section 4.1) and # 3-6 in Fig. 3 (Section 4.2) are executed alternately, the line agent without passenger is deleted, thus the number of agents declines eventually.

4.1 Route Selection of Passenger

In this paper, it is assumed that the user of PTN selects shortest path in time. It means minimizing the first term in Eq. (5). The process of this subsection analyzes the in-vehicle time, waiting time, number of changing bus for all OD pairs (Fig. 3, # 2). The result of the analysis is utilized in the Section 4.2 for computing the evaluation value and for the evolving line agents.

To analyze the route selection of passengers, PTN is converted to the network in Fig. 4 separating bus stops into physical world nodes and virtual nodes.

For instance, since the “line a” and “line b” share the bus stop 3, the figure shows two virtual bus stops, a3 and b3. There are three kind of link and arcs in the converted network. One is “Line Link” connecting virtual bus stops. Second is “Boarding Arc” from physical bus stops to virtual bus stop belonging to lines. Third is “Alighting Arc” from virtual bus stops to physical bus stops. The weight of the “Line Link” is in-vehicle time (Link Length/Moving Speed), “Boarding Arc” is waiting time (Headway/2 representing expectation value of waiting time) and “Alighting Arc” has no weight. Furthermore, to represent a transfer cost, five minutes is added to the weight of the boarding links. (System does not assign the five minutes to the first riding.)

Since the weight of the link and arc in this network is time, shortest path algorithm like Dijkstra Method with heap sort algorithm [8] can immediately find out the shortest paths in travel time.

4.2 Evolution of Bus Line Agent

Evolution rule of line agent changes its transit route and vehicle number. Using the result of the previous subsection, the line agent evolves in selfish to increase the profit defined by the following formula. To encourage the evolution of line agent with higher profit, the target agent is selected in descending order of the profit(# 3 in Fig. 3).

$$P_{L_k} = R_{L_k} - w_2 B_{L_k}$$

(6)
where, $n$ is the evolution step, $R_{L_k}, B_{L_k}$ are user number and vehicle number of line agent $L_k$ respectively. $w_2$ is a control parameter for the relationship between the user number as benefit and the vehicle number as cost. It is expected that small $w_2$ leads to an extension of its transit route to get users and large $w_2$ leads to a shrink of its transit route to reduce vehicle number.

Furthermore, user number, $R_{L_k}$ and vehicle number, $B_{L_k}$ is computed by the following equations.

$$R^e_{L_k} = \sum_{S_i \in L_k} d^e_{S_i, L_k}$$  
$$B^e_{L_k} = \max(B^e_{min}, B^e_{opt}, 1)$$  
$$B^e_{min} = \max_{S_j, S_i \in L_k} (d^e_{S_i, S_j}) Tr_{L_k} CB$$  
$$B^e_{opt} = \sqrt{Tr_{L_k}^e R^e_{L_k}/(2w_1)}$$

where, $d_{i,j}$ is a head-count moving from $i$ to $j$ that is obtained by the user’s route selection analyzed in the previous subsection. $i,j$ stand for the physical bus stops or the virtual bus stop in lines. In case of that $i$ is a physical bus stop and $j$ is a virtual bus stop, it means head-count boarding the line of $j$ at the bus stop $i$. Equation (9) is minimum vehicle number to satisfy the boarding demand and $\max_{S_j, S_i \in L_k} (d^e_{S_i, S_j}) \sum Tr_{L_k} CB$ in the equation is maximum traffic volume among adjacent virtual bus stops $S_j, S_i$ belonging to line agent $L_k$. $Tr_{L_k}$ is a round trip time for line $L_k$. Equation (10) is the vehicle number minimizing the evaluation value of Eq. (5) if Eq. (5) is applied only to the line, $L_k$. Equation (10) is derived from the fact that the evaluation value becomes minimum at the point where the waiting time as user’s cost is same to the vehicle number of operator’s cost [9].

Next step is evolution strategy of target line agent (#4 in Fig. 3). The target line agent, $L_k$, considers all combinations of inclusion of one bus stop not belonging to the line agent, $S_j \notin L_k$, and exclusion of one bus stop belonging to the line agent, $S_i \in L_k$.

All combinations of the target bus stop and operation(inclusion and exclusion) are evaluated by the procedure of following sections. For example, if line b in Fig. 4 becomes target agent, it considers four patterns in Fig. 5. (Exclusion of ST1 is omitted. Because shortest path between ST0 and ST3 runs through ST1.)

4.2.1 Inclusion of bus stop

In case of inclusion of bus stop not belonging to the target line agent, $S_j \notin L_k$, it considers insertion of the bus stop, $S_i \notin L_k$, into the adjacent two bus stops, $S_i, S_{i+1} \in L_k$. (It is also considered that $S_j$ or $S_{i+1}$ is terminal bus stop.) If there are more than one insertion point, it selects the insertion point with minimum increase of the route length. Eventually, the line agent expect the change of the profit, $A_{S_j}$, by the following equation.

$$A_{S_j} = \delta R_{L_k} - w_2(B^{e+1}_{L_k} - B^e_{L_k})$$  
$$\Delta R_{L_k} = \sum_{S_i \in L_k} D^e_{S_i, S_j}$$

where, $D^e_{S_i, S_j}$ is a head-count whose origin bus stop is $S_j \notin L_k$ and destination bus stop is $S_i \in L_k$, given by OD matrix. However, to estimate pure increase of the head-count using $L_k$, $D^e_{S_i, S_j}$, which itinerary includes $L_k$, isn’t computed. The super script, $n + 1$, of $B_{L_k}$, in Eq. (11) means estimated vehicle number after changing route and it is estimated by the following equations.

$$B^{e+1}_{L_k} = \max(B^e_{min}, B^{e+1}_{opt}, 1)$$  
$$B^{e+1}_{opt} = \sqrt{Tr_{L_k}^{e+1} R^e_{L_k}/(2w_1)}$$

where, $Tr_{L_k}^{e+1}$ is a round trip time of vehicle assigned for the target line after inclusion of the bus stop.

4.2.2 Exclusion of bus stop

In case of exclusion of the bus stop belonging to the target line agent, $S_i \in L_k$, the change of the profit, $A_{S_i}$, is computed assuming that the user number utilizing the target line, $L_k$, at the bus stop $S_i$ becomes zero.

$$A_{S_i} = \delta R_{L_k} - w_2(B^{e+1}_{L_k} - B^e_{L_k})$$  
$$\Delta R_{L_k} = -d^e_{S_i, L_k}$$

The vehicle number, $B_{L_k}^{e+1}$, in Eq. (15) is estimation value due to the exclusion of the bus stop $S_i \in L_k$ and it is calculated by Eq. (13) and Eq. (14) with the round trip time $Tr_{L_k}^{e+1}$ after exclusion of the bus stop $S_i \in L_k$.

However, the change of the profit $A_{S_i}$ or $A_{S_j}$ isn’t computed if the following condition is true.

* Inclusion or exclusion of bus stop that violate the whistle-stop tour as prerequisite

* Exclusion of bus stop resulting in isolation of the bus stop from PTN

* Re-inclusion of a bus stop excluded by same line agent

4.2.3 Selection of evolution pattern

The target line agent selects the combination of operation (inclusion or exclusion) and bus stop with maximum change of profit, $\pi$ defined by the following equation. It means greedy strategy.

$$\pi = \max_{S_i, S_j}(A_{S_i}, A_{S_j})$$
However, if $\pi < 0$ is true, the evolution of the target line agent does not take place (arrow from # 5 to “No” in Fig. 3), the target line agent is changed to the agent with next highest profit, $L_{k+1}$ (arrow from # 6 to “No” in Fig. 3).

If evolution of the target line agent, which means inclusion or exclusion of one bus stop described above, took place, process moves to the user’s route selection in the previous subsection 4.1 (arrow from # 5 to “Yes” in Fig. 3).

Eventually the evolution process terminates if all line agents meets with the condition, $\pi < 0$ (arrow from # 6 to “Yes” in Fig. 3).

### 4.3 Modification of Evolution Rule

Results of Section 2.2 clearly states that demand between two stations with large detour decreases sharply if its single efficiency is below 80%. Reflecting the fact into the evolution rule of the line agent, new term was introduced into Eq. (12) for the possibility that demand decreases when line agent tries to include a bus stop involving inefficient detour.

$$
\Delta R_{L_k} = \sum_{S_i \in L_k} D_{S_i, S_i} - r
$$

$$
r = \begin{cases} 
0 & \epsilon \geq 0.8 \\
\epsilon \frac{d^p_{S_i, S_j} + d^p_{S_j, S_i}}{L_{S_i, S_j} + L_{S_j, S_i}} & \epsilon < 0.8 
\end{cases}
$$

$$
\epsilon = r_{S_i, S_j} = 1 \left( L_{S_i, S_j} + L_{S_j, S_i} \right)
$$

where, $\epsilon$ is the single efficiency described in Section 2.2, $L_{S_i, S_j}$ is a network distance between the bus stop $S_i$ and $S_j$, $d^p_{S_i, S_j}$ is a network distance between the bus stop $S_i$ and $S_j$, $L_{S_i, S_j}$ is a straight Euclidean distance between the bus stop $S_i$ and $S_j$. $d^p_{S_i, S_j} + d^p_{S_j, S_i}$ are demands of the bus stop $S_i$ and $S_j$ to use the line $L_k$ at evolution step $n$.

Thus, $r$ means demand reduction of $d^p_{S_i, S_j} + d^p_{S_j, S_i}$ takes place, if large detour between the bus stop $S_i$ and $S_j$ is made by inclusion of the bus stop $S_j$.

### 5. Analysis for Benchmark Problem

#### 5.1 Benchmark Problem

The method in the previous Section 4 is applied to a benchmark problem [10] and it makes clear the advantage and effectiveness of the present method. Figure 6 illustrates an infrastructure network corresponding to street, river, railway network. The number in the node is an ID and the number along side with the link is in-vehicle time in minutes. Table 2 shows the OD demand matrix for one day, that almost every pair of two bus stops have demand. The seating capacity of the vehicle is set to 50 persons.

### 5.2 Analysis Results

In this section, the present method is applied to the benchmark problem. Figure 7 shows evolution history of total travel time (TTT includes, in-vehicle time, waiting time, penalty time for changing vehicle) as user’s cost and total number of vehicle as company’s cost. TTT and vehicle number correspond to the first and second term of Eq. (5). Upper figure shows results of original method with Eq. (12) and lower figure shows results of modified method with Eq. (18) taking into account of the detour effect. The best solution in terms of the evaluation value by Eq. (5) is given at the last step in the lower figure. Both figures show number of vehicle and total travel time decrease as the evolution step advances. The reduction of the total travel time implies that the transit route of surviving line agent becomes sophisticated. However, in case of upper figure without consid-
Table 3 Comparison of results for benchmark problem.

<table>
<thead>
<tr>
<th>Method</th>
<th>Directly (%)</th>
<th>Transfer1 (%)</th>
<th>Transfer2 (%)</th>
<th>Total (hr)</th>
<th>In-Vehicle (hr)</th>
<th>Waiting (hr)</th>
<th>Transfer (hr)</th>
<th>Line Num.</th>
<th>Vehicle Num.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baaj et al. [11]</td>
<td>78.6</td>
<td>21.4</td>
<td>0</td>
<td>3428</td>
<td>2801</td>
<td>349</td>
<td>278</td>
<td>N.A.</td>
<td>89.3</td>
</tr>
<tr>
<td>Mandl [10]</td>
<td>80.0</td>
<td>20.0</td>
<td>0</td>
<td>3511</td>
<td>2818</td>
<td>432</td>
<td>260</td>
<td>N.A.</td>
<td>76.9</td>
</tr>
<tr>
<td>Shih et al. [12]</td>
<td>81.0</td>
<td>19.0</td>
<td>0</td>
<td>3714</td>
<td>3006</td>
<td>462</td>
<td>247</td>
<td>N.A.</td>
<td>82.2</td>
</tr>
<tr>
<td>Zhao [4]</td>
<td>69.9</td>
<td>29.9</td>
<td>0.13</td>
<td>3651</td>
<td>2957</td>
<td>302</td>
<td>392</td>
<td>4</td>
<td>99.3</td>
</tr>
<tr>
<td>This Method, $w_2=5$</td>
<td>$w_1=0.8$</td>
<td>87.7</td>
<td>12.3</td>
<td>3401</td>
<td>N.A.</td>
<td>N.A.</td>
<td>159</td>
<td>8</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>$w_2=9$</td>
<td>99.0</td>
<td>0.90</td>
<td>3272</td>
<td>N.A.</td>
<td>N.A.</td>
<td>13.4</td>
<td>6</td>
<td>77</td>
</tr>
</tbody>
</table>

5.3 Comparison with Other Studies

The comparison between the present method and the previous studies are summarized in Table 3 [4],[10]–[12]. Above three rows of the table represent a rate of passengers in respect to their transit number. The results by the present (modified) method with $w_1=0.8, w_2=5.9$ are described in the column “This Method”. Present method with $w_2=5$ output the minimum travel time (3,244 Hours, 72 Vehicles) and it also output the minimum vehicle number (3,291 Hours, 64 Vehicles) when $w_2=9$. It can be recognized from these results that the present method has potential as an optimization method. Figure 9 shows a generated PTN with smallest total travel time ($w_1=0.8, w_2=5$).

5.4 Discussion

Figure 7 shows that both total travel time and number of vehicle decrease with advancing evolution process and this phenomenon doesn’t depend on the consideration for the detour effect. From this result, it can be concluded that the present MAS has ability to reduce the evaluation value defined by Eq. (5). Furthermore, Fig. 8 shows a trade-off relationship between total travel time and number of vehicle as intended and it can be controlled by the parameter, $w_1$. However, not taking into account of the detour effect, fluctuation of the total travel time around $w_1=0.8$ becomes large in the evolution process. Furthermore, solution with consideration on the detour effect is better than that without consideration of the detour effect and the best solution surpassing previous studies is obtained in case of considering the detour effect. Generally, it can be concluded that modified method considering the detour effect is better than the original method.

In the present method, the number of initial line agents is large (more than 30 line agents are generated as an initial set) and the change in one evolution step is small (inclusion and exclusion of only one bus stop) and passengers generate a selection pressure against the line agents, it can be considered that the combination of these factors becomes the reason why the present method outperforms previous studies.

On the passenger rate in respect to the transit number in Ta-
ble 3, results of the present method is pale against the results of Zhao and it causes slightly large penalty time for transferring. However, TTT of present method is smaller than Zhao’s results. It implies that the line routes generated by the present method are more efficient.

Assuming that a running cost for one vehicle is 30,000 (yen/day) and hourly pay rate is 2000 (yen/person), the value $w_1$ becomes around 15 in Japan. Further more, assuming that a fare is 200 (yen/person) and vehicle running cost is 30,000 (yen/day), the value $w_2$ becomes around 150 in Japan. However, both parameters are controlled to obtain the optimized solutions in our method. Because, the some previous studies also obtain optimized solution by changing the value $w_1$.

6. Conclusion

The problem of generating public transit network (PTN) should be solved in terms of both user and provider and this causes one of the difficulties of the problem. This paper presents new PTN generation method with MAS, in which two agents (i.e., passenger agent and line agent) exists. It is confirmed that the MAS has ability optimizing the evaluation value of PTN defined by total travel time as user’s cost and vehicle number as provider’s cost. Furthermore, it succeeded to output the best solutions surpassing previous studies for the benchmark problem. It is also found that the line agents with considering the detour effect output better solutions than line agents not considering the effect. It is based on the characteristic of passenger’s route selection that was quantitatively clarified with the newly introduced index named to demand weighted efficiency.

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References