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Research on Optimization for Passenger Streamline of Hubs

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Abstract

This paper proposes an optimization model for passenger streamline to promote the organization of hub management. Passengers are divided into two different categories, namely familiar type and unfamiliar type. Then the different route choice behaviors of these two types are analyzed. The graph theory is employed to abstract the hub network. The system cost is taken as the optimization objective, and then an optimization design model for passenger streamline is built. To find a solution, we adopt a traversal search algorithm to enumerate all the possible schemes, and then choose the scheme with the minimum system cost. Finally, a simple case is taken to verify the validity of the proposed model.

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Keywords: passenger hub; passenger streamline; travel behavior; optimization model

1. Introduction

With the expansion of Chinese transportation network, passenger demand in hubs has becoming more and more diversified, especially in integrated passenger hubs. The functions and internal structures of hubs also become more complicated, which brings much trouble to the organization and operation of hubs. Therefore, an optimization model for passenger streamline is proposed to provide a safe, convenient and efficient service in hubs.

Over the past few decades, many researchers have pay attention to passenger hubs (Odoni, 1992; Lemer, 1992; Takagi et al., 2003; Hsu, 2010; Zhao et al., 2011). As one of the most effective way to improve the efficiency of hub operations, the optimization problem of passenger streamline has been widely considered in studies. Daamen (2004)

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proposed a utility model to describe passengers' route choice behavior in hubs, and then gave some strategies to the organization of streamline. Cui and Jia (2006) analyzed the characteristic of passenger streamline and proposed design principles for streamline in integrated traffic terminal. Kaakai et al. (2007) evaluated the streamline of railway transit station with a hybrid Petri nets-based simulation model. O'Kelly (2010) outlined an analytical framework of flow optimization and discussed several variants of the problem. Zhu and Cha (2011) explored the key factors, which effect passengers' efficiency in hubs through analyzing passenger streamline. Although the above studies can assist us in recognizing how the passenger streamline affects the efficiency of hub operations, however, these studies have not introduced available methodologies that can quantitatively optimize the passenger streamline.

Feng (2010) proposed a doubly restricted model for the streamline design problem. The minimum transfer cost and shortest transfer time were taken as optimization objectives. Qi (2011) introduced a concept of measurement entropy of passenger line optimization. The optimization problem was abstracted into a nonlinear constrained problem, which aims at maximizing the measurement entropy. Hu et al. (2012) expanded the study area of passenger streamline into the whole activity process of passengers in hubs. Jiang et al. (2013) proposed a cross entropy method to select passenger streamline from a number of available streamlines. The above-mentioned studies provide valuable methods to optimize passenger streamline. However, their models neglect the different choice behaviors between different types of passengers, which will have a strong effect on the optimization result.

The objective of the paper is to propose an optimization model of passenger streamline with differentiate the route choice behaviors between familiar and unfamiliar passenger. The method of graph theory is employed to abstract hub networks. In the network, nodes represent active points and links represent walkways between nodes.

The remainder of this paper is organized as follows. In Section 2, the different route choice behaviors of familiar and unfamiliar passenger are analyzed. Section 3 describes a modeling approach to optimize passenger streamline. To illustrate the effect of the model, Section 4 presents a numerical result from a simple hub network. Finally, Section 5 concludes the paper.

2. Route choice behavior

In passenger hubs, there have many factors that affect passengers' route choice behavior. Existing researches usually considered some factors such as walking time, crowding penalty and so on. However, in order to judge these factors, passengers must have a long-term travel experience and very familiar with the hub. In fact, there have some passengers who are unfamiliar with the hub, such as tours and shoppers. They usually select the route in a random way. Therefore, it is necessary to classify the passengers, and then analyze their choice behavior respectively.

Based on the description above, passengers can be divided into two types, namely familiar type and unfamiliar type. Familiar passengers have multiple travel experience and can select route by experience. Unfamiliar passengers rarely travel through the hub and select route random.

2.1. Route choice behavior of unfamiliar passenger

Unfamiliar passengers can hardly estimated the general cost of each route. Thus, they will make a random choice in each crossing node, which means the probability that each feasible route, which traverse through node i, selected by unfamiliar passenger will be the same at node i. The probability will equal to the reciprocal of the number of feasible routes:

$$\pi_i^{rs} = 1 \Big/ \sum_{k \in K_{rs}} h_{i,k}^{rs} \tag{1}$$

where K_{rs} denotes the set of available routes when passenger located at origin node r need to walk to destination node s; $h_{i,k}^{rs}$ shows the relationship between node i and route k, let it be one if route k traverses through node i, zero otherwise.

The probability that route k ($k \in K_{rs}$) selected by unfamiliar passenger, who located at origin node r and need to walk to destination node s, can be denoted as:

$$\lambda_k^{rs} = \prod_i \left(\pi_i^{rs}\right)^{h_{i,k}^{rs}} \tag{2}$$

For every route k $(k \in K_{rs})$ satisfy:

$$\sum_{k \in K_{rs}} \lambda_k^{rs} = 1 \quad 0 \le \lambda_k^{rs} \le 1 \tag{3}$$

To illustrate, Fig. 1 displays a hub network with an origin node r, a destination node s and an intermediary node i. In this example, between r and s, there are three available routes k_1, k_2 and k_3. Thus, the probability that route k_1, k_2 or k_3 selected by unfamiliar passenger at node r is equal to 1/3. The probability that route k_2 or k_3 selected by unfamiliar passenger at node i is equal to 1/2. Thus, the probability for each route can be calculated as below: $\lambda_{k_1}^{rs} = 1/3$; $\lambda_{k_2}^{rs} = \lambda_{k_3}^{rs} = 1/3 \cdot 1/2 = 1/6$.

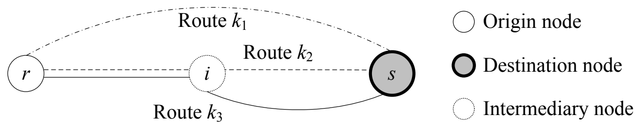


Fig. 1 a hub network with three routes

2.2. Route choice behavior of familiar passenger

Familiar passenger can estimate the general cost of each route, and they will choose route advisably. Let T_k^{rs} denotes the impedance of route k when passenger located at origin node r need to walk to destination node s. It can be calculated with the following equation:

$$T_k^{rs} = \sum_a \delta_{a,k}^{rs} \cdot \left(t_a\left(q_a\right) + u_a\left(q_a\right)\right) \tag{4}$$

where $\delta_{a,k}^{rs}$ shows the relationship between link a and route k, let it be one if route k traverses through link a, zero otherwise; $t_a(q_a)$ shows the travel time in link a; $u_a(q_a)$ shows the crowding penalty in link a. $t_a(q_a)$ and $u_a(q_a)$ can be calculated by

$$t_a(q_a) = t_a(0) \cdot \left[1 + \alpha \left(\frac{q_a}{C_a}\right)^{\beta}\right] \tag{5}$$

$$u_a(q_a) = \begin{cases} 0 & q_a < C_a \\ \mu \left(\dfrac{q_a}{C_a} - 1\right)^{\eta} & q_a \ge C_a \end{cases} \tag{6}$$

where $t_a(0)$ shows the free flow travel time on link a, q_a shows passenger flow on link a, C_a shows the capacity of link a, α and μ are the magnification factors, β and η are the exponential penalty factors.

Thus, the probability that the route k ($k \in K_{rs}$) selected by familiar passenger can be denoted as:

$$p_k^{rs} = \Pr\left(T_k^{rs} \le T_h^{rs}, k \ne h, k \in K_{rs}, h \in K_{rs}\right) \tag{7}$$

For every route k $(k \in K_{rs})$ satisfy:

$$\sum_{k \in K_{rs}} p_k^{rs} = 1 \quad 0 \le p_k^{rs} \le 1 \tag{8}$$

3. Optimization method of passenger streamline

3.1. model formulation

The hub network can be described as a weighted directed graph $G = (V, A)$. V is the set of nodes in the network, which represents the active points in hub, such as the ticket gates and crossings. A is the set of links in the network, which represents walkways between nodes. $R \subseteq V$ and $S \subseteq V$ are the sets of origin and destination nodes respectively.

As a way to improve the efficiency of hub operations, the core of the optimization problem of passenger streamline is to design the streamline with a minimum system cost. Thus, the optimization model of passenger streamline can be formulated as:

$$\min \ z = \sum_a q_a \cdot \left(t_a\left(q_a\right) + u_a\left(q_a\right) \right) \tag{9}$$

s.t.

$$f_{Uf,k}^{rs} = q_{Uf}^{rs} \lambda_k^{rs} \quad \forall k \in K_{rs}, \forall r \in R, \forall s \in S \tag{10}$$

$$f_{Fa,k}^{rs} = q_{Fa}^{rs} p_k^{rs} \quad \forall k \in K_{rs}, \forall r \in R, \forall s \in S \tag{11}$$

$$q_a = \sum_r \sum_s \sum_k (f_{Fa,k}^{rs} + f_{Uf,k}^{rs}) \cdot \delta_{a,k}^{rs} \quad \forall k \in K_{rs}, \forall r \in R, \forall s \in S, \forall a \in A \tag{12}$$

$$\sum_k (f_{Fa,k}^{rs} + f_{Uf,k}^{rs}) = q_{Fa}^{rs} + q_{Uf}^{rs} \quad \forall k \in K_{rs}, \forall r \in R, \forall s \in S \tag{13}$$

$$(f_{Fa,k}^{rs} + f_{Uf,k}^{rs}) \ge 0 \quad \forall k \in K_{rs}, \forall r \in R, \forall s \in S \tag{14}$$

$$\sum_{k \in B_{rs}} n_k^{rs} \ge 1 \ \ and \sum_{k \in B_{rs}/K_{rs}} n_k^{rs} = 0 \quad \forall r \in R, \forall s \in S \tag{15}$$

where q_{Fa}^{rs} and q_{Uf}^{rs} denote demand of familiar and unfamiliar passenger between r and s, respectively; $f_{Fa,k}^{rs}$ and $f_{Uf,k}^{rs}$ denote passenger flow of familiar and unfamiliar passenger between r and s, respectively; B_{rs} denotes the set of routes between r and s; n_k^{rs} is a decision variable, let $n_k^{rs} = 1$ if the route k ($k \in B_{rs}$) is selected into the optimization scheme, zero otherwise; K_{rs} is the subset of B_{rs} and satisfies $K_{rs} = \{ k \mid n_k^{rs} = 1, k \in B_{rs} \}$.

In this model, Equality (10) and (11) determine the passenger flow in route k between r and s. From equality (12), the passenger flow in each link can be calculated. Condition (13) is the flow conservation constraint, and condition (14) is a simply non-negativity constrain. Condition (15) determines that there exist at least one route between r and s.

3.2. Solution method

As the number of OD pair in hub is limited, the set of alternative paths can get easily. Thus, a traversal search algorithm is employed and the calculation procedure is presented as follows.

Step 1. Finding B_{rs}. The set of routes B_{rs} is calculated by k -Shortest path algorithm. Then, unreasonable routes, such as the route traverse through a platform, should be pushed out of B_{rs}.

Step 2. Obtaining the set of optimization scheme. Enumerate all possible schemes based on B_{rs} and the set of optimization schemes of the form $\Theta=\{\Omega_1,\Omega_2,...,\Omega_{Num}\}$, where Ω_m is the m-th scheme and Num is the total number of the schemes.

Step 3. Initializing. Set solution set $Z=\varnothing$, index variable $ST=1$.

Step 4. Calculating the passenger flow in each link. Calculating λ_k^{rs} and p_k^{rs} for each route k ($k \in K_{rs}$) with the ST-th scheme, and then calculating q_a through Eqs. (10)-(12).

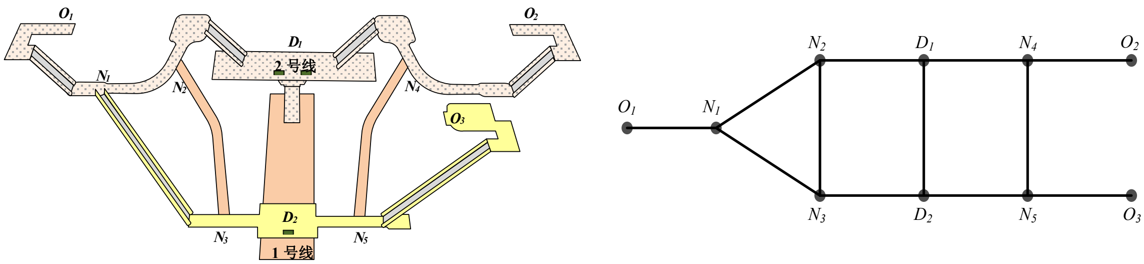
Step 5. Calculating the system cost. Calculating z_{ST}, and then setting $Z=Z\bigcup z_{ST}$.

Step 6. Verifying the stop criterion. If $ST > Num$, stop. Otherwise, set $ST=ST+1$, and go back to Step 4.

Step 7. Finding the optimal solution. Find the minimum value from Z, and the scheme corresponds to is the optimal solution.

4. Numerical result

A metro hub, used in Qi (2011), is adopted to verify the validity of the proposed model. The network is shown in Fig.2. In the hub, there have three entrances O_1, O_2 and O_3 and two metro platforms D_1 and D_2. The topology structure of the hub network is constituted with 10 nodes and 12 lines.



(a) Building structure of the hub (b) The topology structure of the hub

Fig.2 Hub network

The basic circumstance of the test network is shown in Table 1. The passenger demand is shown in Table 2. Assume that $\alpha=0.15$, $\beta=4$, $\mu=0.9$, $\eta=1.5$.

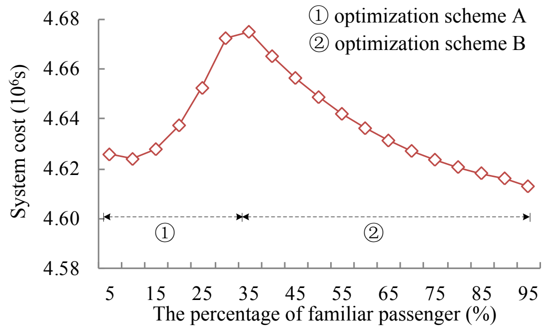
Table 1 Basic circumstance of the test network

Link	Length(m)	$t_a(0)$ (s)	Capacity(p/h)	Link	Length(m)	$t_a(0)$ (s)	Capacity(p/h)
O_1-N_1	30.0	20.0	9420	D_1-D_2	45.0	30.0	14130
N_1-N_2	60.0	40.0	9420	D_1-N_4	60.0	40.0	9420
N_1-N_3	75.0	50.0	9420	D_2-N_5	60.0	40.0	9420
N_2-N_3	37.5	25.0	14130	N_4-N_5	120.0	80.0	14130
N_2-D_1	22.5	15.0	9420	N_4-O_2	50.0	33.3	9420
N_3-D_2	20.0	13.3	9420	N_5-O_3	70.0	46.7	9420

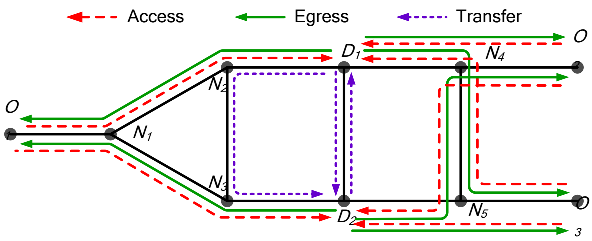
Table 2 Passenger demand *(p/h)*

	O_1	O_2	O_3	D_1	D_2
O_1	-	-	-	1200	1040
O_2	-	-	-	800	960
O_3	-	-	-	720	880
D_1	2560	2400	2320	-	10000
D_2	2080	1920	2000	6000	-

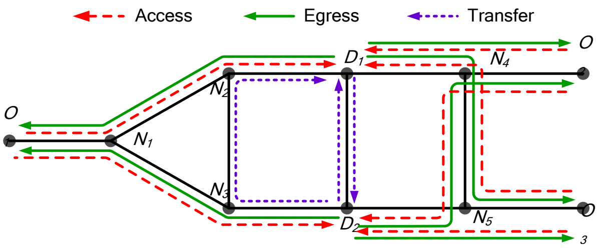
The optimization schemes and system cost are shown in Fig.3. It could be seen that system cost changes with the increase of the percentage of familiar passenger. When the percentage of familiar passenger is lower than 35%, a sharp growth in the system cost can be seen; and the optimization scheme A, shown in Fig.3b, is considered to be an excellent choice. However, the increase trend of the system cost changed after having more than 35% of familiar passenger in hub. A sharp reduction is found in figure and the optimization scheme B, shown in Fig.3c, becomes the optimal solution. It implies that the composition of passengers in hub will have a great effect on the hub efficiency. It is necessary to optimize the passenger streamline based on the route choice behaviors of different type of passengers.



(a) System cost with different percentage of familiar passenger



(b) Optimization scheme A



(c) Optimization scheme B

Fig. 3 Optimization schemes and system cost

5. Conclusion

In this paper, passengers are divided into two types, namely familiar type and unfamiliar type. Different route choice behaviors of these two types are analyzed. For the unfamiliar passenger, a random choice behavior will be adopted in each crossing node. For the familiar passenger, an advisable choice behavior, with the minimum travel impedance, will be adopted at the beginning of the travel.

The hub structure is abstracted as a weighted directed graph. Based on the route choice behaviors of familiar and unfamiliar passenger, an optimization model of passenger streamline is proposed to minimize the system cost. Then, a traversal search algorithm is used to solve the problem. Numerical example shows that the composition of passenger flow will have a significant effect on the system cost and the optimization scheme.

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