Passenger Transportation Structure Optimization Model Based on User Optimum

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Abstract

Passenger transportation structure has a great influence on efficiency of regional comprehensive traffic system. Rationalization and optimization of passenger transportation structure is one of important means of improving its validity. From static point of view, an optimization idea of user optimum in the premise of meeting the demand of regional passenger transportation was put forward. According to this idea, optimization model of passenger transportation structure based on resource constraints is built. With the example of the passenger transportation system in the three cities of Harbin, Daqing and Yichun, model is calculated using the software Matlab. Then the optimized proportions of the comprehensive passenger transportation of the three cities are given. Using fuzzy comprehensive evaluation method, the passenger transportation structures before and after optimization are evaluated. The evaluation method is adopted to estimate the passenger transportation structure which is both from optimization model and the actual situation. Through comparison and analysis of the estimation results, it demonstrated the effectiveness of optimization model.

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1. Introduction

The study on traffic structure optimization firstly appears from the point of "transportation allocation proportion" in urban transportation research center of Chicago, and its main content is making use of different resources to achieve the best combination according to different purposes and convenience [14]. Then, some scholars in traffic

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field propose “transfer curve method”, and it is widely used in practical planning work of subsequent twenty years [10]. As the further research on aggregate model, its deficiency is gradually discovered and scholars begin to study disaggregate model, see [1,2,8,12] cite the “Utility Theory” in economics to build disaggregate model and apply these models to practice based on Probability Theory. They analyze the law of development of comprehensive transportation in China and improve the foreign theoretical methods. Lu and Ma [5,6] introduce the concepts of transportation capacity, energy consumption of ways and environmental capacity and build transportation structure optimization model based on energy consumption in order to determine reasonable traffic structure with least energy consumption. Ma [6] analyze influence factors and development laws of regional comprehensive transportation structure, then she differentiates the traffic areas.

On the basis of referring to predecessors’ research results, this paper puts forward the optimization idea of least resource consumption and optimization model is established [7]. It demonstrates the validity of the established model through the example analysis and fuzzy comprehensive evaluation method.

2. Optimization model of passenger transportation structure

In urban traffic planning thought, the result of logit model is: generalized cost of all users is the least. In view of this, Logit model is applied to the optimization modelling. According to the reference standards when passengers make choice of transportation means, it builds the generalized cost function C. Passengers make their choice of transportation means which is of the least generalized cost, see Ruth [9] and Stephen et al. [11]. $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ are assumed as the weights of each influence factor, so generalized cost function can be simplified as (1):

$$C = \lambda_D C_D + \lambda_C C_C + \lambda_T C_T + \lambda_E C_E$$

Where $C_D$ is Trip cost; Trip time is $C_T$; Trip comfort is $C_C$; Trip safety $C_T$ is Trip convenience.

Passengers are divided into $n$ classes according to certain economic characteristics. There are $m$ kinds of means of transportation for passengers to choose. In order to show passengers’ behaviors of choosing means of transportation, the paper quotes the random utility theory—utility function, and makes it as $M$. Utility function and generalized cost function are negative functions, It is given by:

$$M_{ik} = -C_{ik} + \epsilon_{ik}$$

Where $M_{ik}$ is the utility function when the $k$ kind of passengers choose the $i$ kind of means of passenger transportation, $C_{ik}$ is the generalized cost function when the $k$ kind of passengers choose the $i$ kind of means of passenger transportation, and $\epsilon_{ik}$ is the random items, due to the non-deterministic utility caused by error, $i=1,2,\ldots,m, k=1,2,\ldots,n$.

Passengers choose some means of transportation based on their own minds that utility value of their means of transportation is larger than another one, see Lejoon [4]. Probability function can be expressed as:

$$P_{ik} = P\{M_{ik} \geq M_{jk}, \forall i \neq j, i = 1,2,\ldots,m\}$$

$$= P\{C_{ik} + \epsilon_{ik} \geq C_{jk} + \epsilon_{jk}\}$$

$$= P\{\epsilon_{jk} \leq C_{ik} + \epsilon_{ik} - C_{jk}\}$$

$$= \int_{\epsilon_{ik}} F\{C_{ik} - C_{jk} + \epsilon_{ik}\} \cdot f_{\epsilon_{ik}}(y)dy$$

Where $F\{\}$ is the joint distribution function of random item $\epsilon_i; f_{\epsilon_{ik}}(y)$ is the density function of random item $\epsilon_i$.

Generally $\epsilon_i$ is assumed to obey negative exponential distribution and is independent of each other. When $k$ passenger chooses $i$ mean of passenger transportation, the probability is:
\[ P_{ik} = \frac{e^{C_{ik}}}{\sum_i e^{C_{ik}}} \]  

This model is applied to the system of regional comprehensive passenger transportation and passenger traffic volume of whole region is \( Q \). If there are \( i \) kinds of means of passenger transportation between the place \( m \) and \( n \), thus its passenger volume is:

\[ Q_{mn}^{im} = Q_{mn}^{im} \cdot P_{ik} = Q_{mn}^{im} \cdot \frac{e^{C_{ik}}}{\sum_i e^{C_{ik}}} \]  

The volume of the \( i \) kind of mean of transportation in the whole region is:

\[ Q_i = \sum_m \sum_n Q_{mn}^{im} \cdot \frac{e^{C_{ik}}}{\sum_i e^{C_{ik}}} \]  

3. Application

Paper analyzes the case of three cities: Harbin, Daqing and Yichun in Heilongjiang Province. The cost, time, comfort, safety and convenience of railway, highway, and aviation among the three cities are known by investigation. Using the optimization method proposed above, it analyzes the adaptation of the current structure of the regional comprehensive passenger transportation.

3.1. Data disposal

Research areas include Harbin, Daqing and Yichun. Based on actual data of survey and historical data, it can get the actual passenger volume of different means of transportation among the three cities, as shown in Table 1 and fares between different cities as shown in Table 2.

| Interval       | Railway | Highway | Aviation |
|----------------|---------|---------|----------|
| Harbin-Daqing  | 17123   | 2850    | 30       |
| Harbin-Yichun  | 3610    | 650     | 51       |
| Daqing-Yichun  | 995     | 410     | —        |
| Daqing-Harbin  | 18346   | 2156    | 66       |
| Yichun-Harbin  | 3015    | 1546    | 43       |
| Yichun-Daqing  | 879     | 315     | —        |

| City          | Highway | Rail | Aviation | Highway | Rail | Aviation | Highway | Rail | Aviation |
|---------------|---------|------|----------|---------|------|----------|---------|------|----------|
| Harbin        | —       | —    | —        | 34      | 20   | 700      | 74      | 42   | 530      |
| Daqing        | 34      | 20   | 700      | —       | —    | —        | 79.5    | 43   | —        |
| Yichun        | 74      | 42   | 530      | 79.5    | 43   | —        | —       | —    | —        |

For comparative calculation, it should standardize data with the formula (7) to transform, as shown in Table 3.
\[ Z'_i = \frac{Z_i}{\max\left(Z^i_1, Z^i_2, Z^i_3\right)}, i = 1, 2, 3, j = 1, 2, 3 \] (7)

Table 3. Dimensionless transformation of fares.

| City     | Harbin | Daqing | Yichun |
|----------|--------|--------|--------|
|          | Highway | Rail   | Aviation | Highway | Rail   | Aviation | Highway | Rail   | Aviation |
| Harbin   | —       | —      | —       | 0.049   | 0.029  | 1       | 0.106   | 0.06   | 0.757    |
| Daqing   | 0.049   | 0.029  | 1       | —       | —      | —       | 0.114   | 0.061  | —        |
| Yichun   | 0.106   | 0.06   | 0.757   | 0.114   | 0.061  | —       | —       | —      | —        |

Combined with the result of questionnaire, the same can gain dimensionless values of time, comfort, safety and convenience, respectively as shown in Table 4 to Table 7.

Table 4. Dimensionless transformation of time.

| City     | Harbin | Daqing | Yichun |
|----------|--------|--------|--------|
|          | Highway | Rail   | Aviation | Highway | Rail   | Aviation | Highway | Rail   | Aviation |
| Harbin   | —       | —      | —       | 0.103   | 0.138  | 0.069   | 0.517   | 0.579  | 0.069    |
| Daqing   | 0.103   | 0.138  | 0.069   | —       | —      | —       | 0.69    | 1      | —        |
| Yichun   | 0.517   | 0.579  | 0.069   | 0.69    | 1      | —       | —       | —      | —        |

Table 5. Dimensionless transformation of comfort.

| City     | Harbin | Daqing | Yichun |
|----------|--------|--------|--------|
|          | Highway | Rail   | Aviation | Highway | Rail   | Aviation | Highway | Rail   | Aviation |
| Harbin   | —       | —      | —       | 0.663   | 0.59   | 1       | 0.651   | 0.578  | 0.988    |
| Daqing   | 0.663   | 0.59   | 1       | —       | —      | —       | 0.663   | 0.602  | —        |
| Yichun   | 0.651   | 0.578  | 0.988   | 0.663   | 0.602  | —       | —       | —      | —        |

Table 6. Dimensionless transformation of safety.

| City     | Harbin | Daqing | Yichun |
|----------|--------|--------|--------|
|          | Highway | Rail   | Aviation | Highway | Rail   | Aviation | Highway | Rail   | Aviation |
| Harbin   | —       | —      | —       | 0.879   | 0.99   | 0.97    | 0.859   | 1      | 0.96     |
| Daqing   | 0.879   | 0.99   | 0.97    | —       | —      | —       | 0.859   | 0.99   | —        |
| Yichun   | 0.859   | 1      | 0.96    | 0.859   | 0.99   | —       | —       | —      | —        |

Table 7. Dimensionless transformation of convenience.

| City     | Harbin | Daqing | Yichun |
|----------|--------|--------|--------|
|          | Highway | Rail   | Aviation | Highway | Rail   | Aviation | Highway | Rail   | Aviation |
| Harbin   | —       | —      | —       | 0.901   | 0.604  | 1       | 0.934   | 0.582  | 0.967    |
| Daqing   | 0.901   | 0.604  | 1       | —       | —      | —       | 0.901   | 0.549  | —        |
| Yichun   | 0.934   | 0.582  | 0.967   | 0.901   | 0.549  | —       | —       | —      | —        |

The above calculation results are put into formula (1) and the corresponding values can be obtained. According to the above data, the generalized cost function of different income groups with different transportation means can be calculated to, and it can be directly applied to the optimization model based on user optimum. Supply capacity between two cites of the three are shown in Table 8.
3.2. Model calculation

By using optimization toolbox in Matlab, it works out the sharing rate of passenger transportation of the three cities with the optimization model based on user optimum. The results are shown in Table 9.

| Interval          | Railway Supply | Highway Supply | Aviation Supply |
|-------------------|----------------|----------------|-----------------|
| Harbin-Daqing     | 30 21480       | 61 3050        | 1 180           |
| Harbin-Yichun     | 4 3222         | 13 650         | 1 180           |
| Daqing-Yichun     | 1 1074         | 2 100          | —               |
| Daqing-Harbin     | 29 20406       | 22 1100        | 1 180           |
| Yichun-Harbin     | 4 3222         | 21 1050        | 1 180           |
| Yichun-Daqing     | 1 1074         | 2 100          | —               |

Table 8. Supply of passenger transportation between two cities.

| Interval          | Railway Frequency | Highway Frequency | Aviation Frequency |
|-------------------|-------------------|-------------------|-------------------|
| Harbin-Daqing     | 0.435             | 0.529             | 0.036             |
| Harbin-Yichun     | 0.523             | 0.409             | 0.068             |
| Daqing-Yichun     | 0.496             | 0.504             | —                 |

Table 9. Sharing rate from the optimization model based on user optimum.

3.3. Model test

There are many methods can be used for evaluation of passenger transportation structure and Analytic Hierarchy Process (AHP) is suitable for problem in different levels and fuzzy mathematics has good expression on the problem difficult to use quantitative analysis [13]. So a combination of the two methods can more objectively and accurately evaluate rationality of passenger transportation structure.

With an example of optimization results of passenger transportation structure from Harbin to Daqing, its proportion is: railway 0.431, highway 0.521 and aviation 0.018. The comparison with the present situation is shown as Table 10 and Fig. 1.

| Interval          | Railway | Highway | Aviation |
|-------------------|---------|---------|----------|
| Before optimization | 0.372   | 0.586   | 0.042    |
| After optimization  | 0.435   | 0.529   | 0.036    |

Table 10. Comparison before and after optimization.

By contrasting the before proportion with the optimized result, it shows the proportion of railway increases 16.94%, highway decreases 9.73%, and airlines decreases 14.29%.

Fuzzy comprehensive evaluation is used and its process is as follows. According to the established evaluation index system of passenger transportation, factor sets can be determined as:

\[ U = \{ U_1, U_2, U_3, U_4 \} = (\text{economy, society, ecology, technology}) \]

\[ U_1 = (\text{transportation cost, payback period of investment, infrastructure investment, profit margin of cost}) \]

\[ U_2 = (\text{fitness with economic development, ability to meet the demand of transportation, comfort, resident sensitivity}) \]

\[ U_3 = (\text{energy consumption, occupancy rate of land resource, air pollution, noise pollution}) \]

\[ U_4 = (\text{density of road network, speed, security, network adaptability}) \]

Evaluation set of seven grades: \[ V = \{ \text{excellent +, excellent -, good +, good -, medium, poor, very poor} \} \]

Weights of different evaluation index in each layer are obtained by using AHP:

\[ W = \{ W_1, W_2, W_3, W_4 \} = (0.531, 0.245, 0.152, 0.072) \]

Level values of concrete indexes of highway, railway and aviation can be obtained through analysis as shown in Table 11 and 12.
According to the above-mentioned value and passenger transportation structure before and after optimization, weight values of each index before and after optimization can be determined as follows:

Results before optimization:
\[ V_1 = \{v_{11}, v_{12}, v_{13}, v_{14}\} = \{0.240, 0.314, 0.137, 0.309\}, \quad V_2 = \{v_{21}, v_{22}, v_{23}, v_{24}\} = \{0.114, 0.277, 0.363, 0.246\}, \]
\[ V_3 = \{v_{31}, v_{32}, v_{33}, v_{34}\} = \{0.508, 0.103, 0.065, 0.324\}, \quad V_4 = \{v_{41}, v_{42}, v_{43}, v_{44}\} = \{0.425, 0.149, 0.091, 0.335\}. \]

Results after optimization:
\[ W_1 = \{w_{11}, w_{12}, w_{13}, w_{14}\} = \{0.317, 0.221, 0.354, 0.108\}, \quad W_2 = \{w_{21}, w_{22}, w_{23}, w_{24}\} = \{0.267, 0.315, 0.245, 0.173\}, \]
\[ W_3 = \{w_{31}, w_{32}, w_{33}, w_{34}\} = \{0.466, 0.161, 0.277, 0.096\}, \quad W_4 = \{w_{41}, w_{42}, w_{43}, w_{44}\} = \{0.422, 0.125, 0.303, 0.150\}. \]

Membership degree of influence factors can be determined by Delphi method. As Table 13 shown.

By calculation, the final fuzzy evaluation sets before optimization is \((0.136, 0.143, 0.162, 0.171, 0.227, 0.114, 0.047)\), the optimized fuzzy evaluation sets is \((0.173, 0.279, 0.206, 0.149, 0.062, 0.082, 0.049)\). According to maximum membership degree method, passenger transportation structure of Harbin-Daqing is "medium" before optimization and "excellent-" after optimization and three grades are promoted.
Namely, the comprehensive performance of optimized passenger transportation structure is improved in aspects of economy, society, ecology and technology, and it is more suitable for social development and can provide effective references for planners.

Table 13. Membership degree of each influence factor.

| Influence factor | Sub-index                      | Membership degree |
|------------------|-------------------------------|-------------------|
| Main index       |                               | \( V_{11} \) \( V_{12} \) \( V_{13} \) \( V_{14} \) \( V_{15} \) |
| Economy          | Cost                          | 0.53 0.16 0.10 0.20 0.01 |
|                  | Investment                    | 0.32 0.14 0.28 0.19 0.07 |
|                  | Payback period                | 0.74 0.22 0.04 0 0 |
|                  | Profit margin of cost         | 0.39 0.26 0.32 0.03 0 |
|                  | Social fitness                | 0.48 0.32 0.15 0.05 0 |
| Society          | Ability to meet the Demand    | 0.32 0.43 0.2 0.04 0.01 |
|                  | Comfort                       | 0.45 0.25 0.2 0.07 0.03 |
|                  | Resident sensitivity          | 0.38 0.32 0.22 0.05 0.03 |
|                  | Energy dissipation            | 0.53 0.16 0.10 0.2 0.01 |
|                  | Land occupancy rate           | 0.32 0.14 0.28 0.19 0.07 |
| Ecology          | Air pollution                 | 0.74 0.22 0.04 0 0 |
|                  | Noise pollution               | 0.39 0.26 0.32 0.03 0 |
|                  | Road density                  | 0.56 0.32 0.1 0.02 0 |
| Technology       | Operation speed               | 0.28 0.33 0.24 0.12 0.03 |
|                  | Safety                        | 0.5 0.32 0.14 0.02 0.02 |
|                  | Adaptation                    | 0.42 0.25 0.18 0.11 0.04 |

4. Conclusion

From the perspective of user optimum, combined with cost, time, safety, comfort and convenience of passengers, the generalized cost function is established. By using probability distribution function, optimization model of passenger transportation structure is built based on user optimum.

With an example of the passenger transportation system in the three cities of Harbin, Daqing and Yichun, the optimization model established is simulated and calculated with Matlab which includes data sorting, dimensionless processing, utility function calculating and so on. Then the optimized proportions of the comprehensive passenger transportation of the three cities are obtained.

According to characteristics of passenger transportation structure, the evaluation index system of passenger transportation structure is established. Using fuzzy comprehensive evaluation method, the passenger transportation structures before and after optimization are evaluated. Finally it demonstrates the validity of the optimization model by comparing and analyzing the evaluation results.

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