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Evaluation of Public Transportation Operation Based on Data Envelopment Analysis

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Abstract

This paper presented method on evaluating the performance of bus routes within a public transportation system using revised DEA method and sensitivity analysis of indexes. First, based on the analysis of the operation of public transportation, passenger load rate, service reliability, average dwell time and average running speed were chosen as output indexes, a virtual index as input from the operators' and passengers' perspective. Then the method is applied to 3 bus routes of Beijing public transportation system and the improvement suggestions are put forward. Finally, the results which show that the operation in off-peak period are better than that in peak period, and average running time and service reliability are the key factors influencing performance, conform to the reality of the city, thus validating the practicality of the method. In sum, this study is helpful for improving the operation of public transportation system.

Keywords: public transportation; evaluation indexes; data envelopment analysis (DEA)

1. Introduction

Developing public transportation systems is one of the main ways to reduce congestion. As a result the "bus priority" has been widely accepted in China. In general, the level of service of public transportation in China is relatively low, and there are some significant problems in the public transportation system of metropolis, such as

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Beijing. For instance, during the off-peak period, the passenger load rate is relatively low due to the high frequency; whereas during the peak period, the passengers' waiting time are relatively long, and features frequent bunching and low speed. Thus, evaluating and analyzing the public transportation operation accurately and solving existing key problems identified are crucial issues, which is beneficial for the planning, design and operation of public transportation system.

Currently, the above problems have encouraged researches focusing on the evaluation of public transportation operation. The main methods include fuzzy evaluation, analytic hierarchy process (AHP), BP artificial neural network, and clustering analysis, etc. Among them, fuzzy evaluation and AHP may result in inaccurate results with weighted subjectively. In addition, BP artificial neural network and clustering analysis require a great deal of statistical data.

Data Envelopment Analysis (DEA) is a nonparametric method, which emphasizes the objectivity and is easy to use. DEA is widely used in efficiency evaluation; however, it's seldom applied in operation evaluation of public transportation systems due to the problems of data collection, index selection and quantification.

This paper uses the revised DEA method to evaluate the operation of bus routes with GPS and passenger flow data. Bus routes which need to be improved are identified, and suggestions for improvements s are proposed.

2. Methodology

2.1. Index selection

Index selection, which is the key step to evaluate the performance of bus routes accurately, need to follow some basic principles as follows:

- Select indexes that can be obtained easily in practice.
- Select indexes that can reflect the characteristics of performance of bus routes comprehensively and objectively.
- Select key indexes as few as possible to reveal the main features of bus routes.

- In addition, the input and output of DEA also should meet the following requirements:

- The input/output values which should be positive.
- The number of inputs and outputs should not exceed the number of half of the evaluation object.

The public transportation system is complex, involving vehicles, road conditions, and time-varying passenger flow. The evaluation index system of public transportation was established based on the current situation of public transportation system in China. Six aspects – safety, speediness, punctuality, comfort, economy and convenience, from the operators' and passengers' perspectives, are included as shown in Fig. 1.

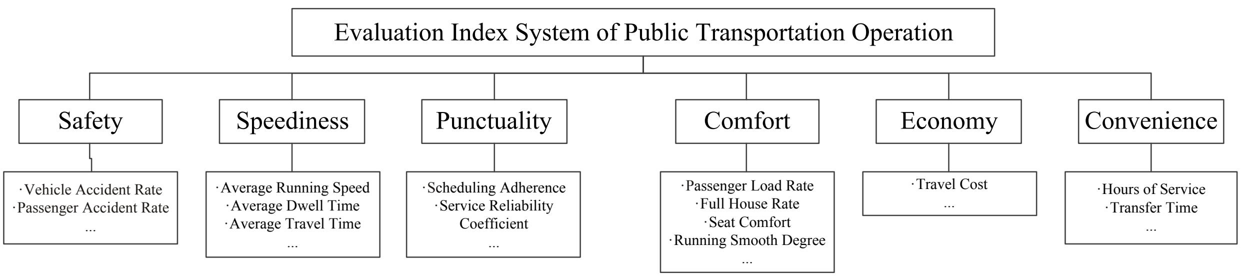

Fig. 1. Evaluation index system of public transportation operation

Some of the above indexes can be directly quantified, while others cannot. After a comprehensive consideration of data acquisition and index calculation, four indexes were selected as follows:

- *Service reliability.* It attracts passengers' and operators' attention, which refers to headway fluctuations of the buses. Moreover, even though scheduling adherence is also a key index, it isn't selected since the data is difficult to obtain and passengers mainly focus on headway fluctuations rather than headways in the situation that the departure interval of urban buses are generally less than 10 minutes.
- *Average running speed.* It reflects the buses' speediness.
- *Average dwell time*. It reflects the buses' stop time at stations.
- *Passenger load rate.* It reflects the economy of bus operation and the comfort of passengers. A lower one will be accepted by passengers, and a higher one means more income for operators. It is an important index which can be obtained easily related with sanitary conditions, seat comfort, and riding comfort.

2.2. Model

DEA is an optimization-based technique widely used to measure relative efficiencies. Due to non-parametric model Characteristics and its ability to combine multiple inputs and outputs, DEA has been found an effective tool if used appropriately. A few of the characteristics of DEA are:

- DEA does not need the index weight be given in advance, and it can avoid subjective evaluation.
- DEA does not require an assumption of a function of inputs and outputs.
- It is convenient to deal with the inputs and outputs data, for these data can have different units.

For the traditional DEA method, inputs and outputs can be related with each other by certain economic relations. However, the indexes of public transportation operation don't have the similar relationship. For this reason, all indexes were defined as outputs, and a virtual input was defined.

For the self-evaluation of the traditional DEA method, the evaluation objects will search the most favorable weight combination for themselves. As a result, cross model was introduced in order to make the results more accurate.

Further, understanding the influence of each index is important. It not only helps to understand the change of evaluation results due to the change of indexes, but also helps to provide improvement suggestions. Therefore, the sensitivity analysis of indexes was conducted in this paper.

2.2.1. Operation evaluation model

Assume there are R decision-making units (DMUs), and each DMU has one input and four outputs. The DMU_k is one of R DMUs ($1 \le k \le R$), and the input is denoted by X_i^k (i=1). Four outputs are denoted by Y_j^k (j=1，2，3，and 4). The purpose of DEA is to construct a frontier that envelops all data points representing the efficiency of all DMUs under consideration and to calculate the efficiency score for each DMU_k. The problem of determining the efficiency score E_k for DMU_k can be formulated in the following linear programming problem:

$$
\begin{aligned}
\max E_K &= \frac{\sum_{j=1}^{n} u_j^k Y_j^k}{\sum_{i=1}^{m} v_j^k X_i^k} \\
s.t. \ \frac{\sum_{j=1}^{n} u_j^k Y_j^r}{\sum_{i=1}^{m} v_j^k X_i^k} &\le 1,\ r = 1,2,\ldots,R \\
u_j^k &\ge \varepsilon \succ 0,\ j = 1,2,3,4 \\
v_i^k &\ge \varepsilon \succ 0,\ i = 1
\end{aligned}
\tag{1}
$$

where u_j^k is a decision variable representing the weight for output j, under the goal of maximizing E_k;
v_i^k is a decision variable representing the weight for input i, under the goal of maximizing E_k;
and ε is a non-Archimedean number.

The steps of using the cross model are as follows:

Step 1: calculate the most favorable weight combination u_j^r , v_i^r for each DMU_r with the above model.

Step 2: calculate R-1 efficiency scores E_k^r with other R-1 most favorable weight combinations u_j^r , v_i^r (r ≠ k). The formula is shown as follows:

$$E_k^r = \frac{\sum_{j=1}^{n} u_j^r Y_j^k}{\sum_{i=1}^{m} v_i^r X_i^k} \tag{2}$$

where E_k^r is the efficiency score of DMU_k , which is calculated using the most favorable weight combinations u_j^r , v_i^r of DMU_r.

Step 3: calculate the arithmetic average of E_k^r as the cross efficiency score of DMU_k, CE_k:

$$CE_k = \frac{\sum_{r=1}^{R} E_k^r}{R-1}, r \neq k \tag{3}$$

Step 4: calculate the average efficiency score of DMU_k, AE_k:

$$AE_k = \frac{(R-1)CE_k + E_k}{R} \tag{4}$$

The value of AE_k ranges from 0 to 1. And greater value of AE_k implies better operation of DMU_k. In contrast, smaller value of AE_k means worse operation of DMU_k.

2.2.2. Sensitivity analysis of indexes model

Assume D is an evaluation index system, and D_j is defined as the system which removes the index j. $Z_k(D)$ represents the efficiency scores of DMU_k which is calculated with D, and $Z_k(D_j)$ represents the efficiency scores of DMU_k which is calculated with D_j. Then the influence coefficient of index j, $S_k(D_j)$, can be calculated as follows:

$$S_k(D_j) = \frac{Z_k(D) - Z_k(D_j)}{Z_k(D_j)}, k = 1,2,\ldots,R, j = 1,2,3,4 \tag{5}$$

$\sum S_k(D_j)$ is obtained by adding the influence coefficient of index *j*, $S_k(D_j)$. And greater value of $\sum S_k(D_j)$ implies bigger influence of index *j* (i.e. higher sensitivity). In contrast, smaller value of $\sum S_k(D_j)$ means smaller influence of index *j* (i.e. lower sensitivity).

3. Case Study

The bus routes 16, 87, 105 in Beijing were chosen as study cases in this paper. The data on each Thursday were collected from March 8, 2012 to March 22, 2012 by GPS and manual counting. During the study period, no major weather issues that might have affected the operation of public transportation systems occurred.

3.1. Data

With the processing of GPS data and passenger flow data, corresponding values of operation evaluation indexes were obtained, as indicated in Table 1.

Table 1. Statistics of operation evaluation indexes

Line/ Direction	Period	Passenger load rate	Service reliability	Average dwell time (s)	Average running speed (km/h)
16/A	Peak	1.06	1.77	29.18	16.72
16/B		0.87	5.34	22.53	18.18
16/A	Off-peak	0.50	7.76	18.05	20.06
16/B		0.44	5.82	18.65	21.15
87/A	Peak	0.74	2.41	24.41	16.62
87/B		0.70	2.64	32.60	18.57
87/A	Off-peak	0.64	7.91	23.89	20.93
87/B		0.53	3.54	23.92	22.21
105/A	Peak	0.81	2.71	43.50	9.63
105/B		1.06	1.94	34.63	12.90
105/A	Off-peak	0.68	3.87	33.45	13.65
105/B		0.68	2.78	31.75	14.47
Average	Peak	0.87	2.80	31.14	15.44
	Off-peak	0.58	5.28	24.95	18.75

Considering the principles of selecting indexes (i.e. smaller input indexes are better, whereas greater output indexes are optimal), two of four indexes were transformed as follows:

- *Passenger load rate*. The problem concerning what kind of passenger load rate is the best has been studied by previous researches without any firm conclusion being reached. Based on field data, the most appropriate passenger load rate is 0.6 in this paper. And passenger load rate index was introduced, and its transformation process was as follows: passenger load rate was defined as a passenger load rate index as A. When a = 0.6, A = 100; When a = max |a-0.6|, A = 0. Moreover, the values were determined in a linear relationship.
- *Average dwell time*. Average dwell time index was introduced, its transformation process was as follows: we define t as average dwell time and T as average dwell time index. When t = max t, T = 0; When t = min t, T = 100. The values were determined in a linear relationship as well.

Besides, in this paper defined a virtual input index, and its value is 1. Accordingly, Table 2 displays the values of input-output indexes.

Table 2. Data of input – output indexes

Route/ Direction	Period	Y1*	Y2*	Y3*	Y4*	X1*
16/A	Peak	1.50	1.77	56.28	16.72	1.00
16/B		42.06	5.34	82.41	18.18	1.00
16/A	Off-peak	77.06	7.76	100.00	20.06	1.00
16/B		64.50	5.82	97.64	21.15	1.00
87/A	Peak	69.32	2.41	75.00	16.62	1.00
87/B		79.61	2.64	42.81	18.57	1.00
87/A	Off-peak	92.04	7.91	77.04	20.93	1.00
87/B		84.48	3.54	76.94	22.21	1.00
105/A	Peak	54.79	2.71	0.00	9.63	1.00
105/B		0.00	1.94	34.87	12.90	1.00
105/A	Off-peak	83.66	3.87	39.50	13.65	1.00
105/B		83.44	2.78	46.16	14.47	1.00

*denotes that Y1 is the Passenger load rate index, Y2 is the Service reliability, Y3 is the Average dwell time index, Y4 is the Average running speed, and X1 is the virtual input index.

3.2. Results and analysis

The software MATLAB was used to solve the formulated linear programming problems. Table 3 displays the results indicating the operational performance and the sensitivity of indexes for each route/direction. It can be observed that the operation for each route/direction in its off-peak period is better than that in its peak period. Route 87/A is the best during the off-peak period, and its AE_k is 0.954, which is close to 1. Whereas route 105/B is the worst during the peak period, and its AE_k is 0.268. Therefore, in depth analysis on route 105 is conducted and suggestions for improvement are proposed. Furthermore, indexes Y4 and Y2 are relatively larger for route 105, and their $\sum S_k(D_j)$ are 1.146 and 0.872. Accordingly, average running speed and service reliability, which represented by indexes Y4 and Y2, can be identified as the key factors that influence performance.

According to the calculated results (Table 3) and statistics of operation evaluation indexes (Table 1), conclusions can be obtained as follows.

Firstly, during the off-peak period, the average running speed of route, which is 13.65km/h and 14.47km/h for 105/A and route 105/B respectively, are far below the average of all bus routes, 18.75 km/h. During the peak period, the index values of this route, which is 9.63km/h and 12.90km/h respectively, are below the average of all bus routes, 15.44 km/h.

Secondly, during the off-peak period, the service reliability which are 3.87 and 2.78 for line 105/A and route 105/B respectively, are smaller than the average of bus routes, 5.28. During the peak period, the index values of this route, which are 2.71 and 1.94 respectively, are below the average of bus routes, 2.80.

Thirdly, it's believed that if the value of service reliability is lower than 2, bunching would occur, because the fluctuation of gap between arrive interval and departure interval has reached 50% of the departure interval. Bunching may easily happen for route 105 during the peak period.

Fourthly, the reason leading to the above results has two aspects. One reason is that the layout of route 105 has nearly one-third of its route on collector streets and minor roads, where the road conditions are bad, with narrow roads and serious mixed traffic flow. Another reason is that the layout of route 105 is mainly inside the 2nd Ring and goes through the political and financial center in Xicheng district, where there are many signal intersections.

Table 3. The evaluation results for bus routes

Route/ Direction	Period	Sensitivity analysis of indexes				Operation evaluation	
		Remove Y1	Remove Y2	Remove Y3	Remove Y4	AE_k	Rank
16/A	Peak	0.000	0.000	0.000	0.338	0.364	11
16/B		0.008	0.000	0.017	0.048	0.658	9
16/A	Off-peak	0.000	0.000	0.019	0.000	0.911	2
16/B		0.000	0.000	0.017	0.024	0.844	4

87/A	Peak	0.137	0.062	0.070	0.000	0.687	6
87/B		0.129	0.050	0.000	0.015	0.744	5
87/A	Off-peak	0.000	0.000	0.000	0.000	0.954	1
87/B		0.000	0.000	0.000	0.057	0.879	3
105/A	Peak	0.000	0.328	0.000	0.000	0.398	10
105/B		0.000	0.000	0.000	0.665	0.268	12
105/A	Off-peak	0.011	0.235	0.000	0.000	0.672	8
105/B		0.011	0.197	0.000	0.000	0.678	7
$\sum S_k(D_j)$		0.296	0.872	0.123	1.146	--	--

Therefore, improving the running environment is essential, and can be realized through the following two measures:

- Provide the bus route with transit signal priority (TSP) and fewer intersections if possible.
- Separate the mixed traffic flow. Deploy exclusive bus lanes when road conditions allow.

Additionally, implementing real-time scheduling actively is also helpful to ensure better service quality.

4. Conclusions

In this paper, the evaluation index system of public transportation operation is established by selecting four key indexes, including passenger load rate, service reliability, average dwell time, and average running speed. Then operation evaluation model are built and sensitivity analysis of indexes model are conducted. The case study shows that the method has good applicability, and can be used to improve the operation of public transportation system. Nevertheless, the DEA method has relative evaluation result. Hence, the route with a good evaluation result may still require improvements. This problem can be solved by adding evaluation objects or determining the index expectations using the Delphi method.

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