Research on Energy Efficiency Evaluation of Urban Rail Transit Based on DEA-BCC Model

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Abstract. The scale of urban rail transit network has been expanding in recent years, and the energy consumption of urban rail transit systems is also growing. So the paper intends to study on energy efficiency of urban rail transit so as to help enterprises to reduce energy consumption and operation costs. From the perspective of economics, the paper establishes an evaluation index system for energy efficiency of urban rail transit with multi-inputs and outputs. Then DEA-BCC model is proposed to evaluate the energy efficiency of urban rail transit, and the empirical analysis of Beijing subway Line5, Line15 and Batong Line is carried out to verify its rationality, which aims to find the influencing factors of energy efficiency of urban rail transit from efficiency and slack variable. Last, some suggestions on how to improve energy efficiency of urban rail transit system are given in the paper.

1. Introduction

By the end of 2018, urban rail transit (hereinafter referred to as the URT) has been operated in 35 cities in China, including 185 operating lines and total length 5761.4 km. With the expansion of URT network, the demand for energy resources is also increasing. According to statistics, 90% of the energy consumed by URT is electricity [1]. How to improve the energy efficiency of URT has been paid more and more attention. To evaluate the energy efficiency of URT not only can help relieve the pressure of urban electricity consumption, but also can help URT enterprises to save electricity and reduce operation costs. But at present, there were relatively few researches on the energy efficiency of URT, and the evaluation index systems for energy efficiency were not uniform.

Most scholars believed that the connotation of energy-saving was same as energy efficiency essentially. From the perspective of economics, Chinese scholars defined energy efficiency as the ratio between the services provided for terminals and the total amount of energy consumed. In Ref. [2], Y J Shi analyzed the influencing factors of urban rail energy consumption from seven aspects: time, region, station, vehicle, equipments, seasons and proportion of line’s energy saving slope. In Ref. [3], H Y Wang modeled three power systems of subway station, ventilation system, power lighting system and escalator, so as to analyze the influencing factors of urban rail energy consumption. In Ref. [4], Y Chen found that train weight, unit basic resistance and traction motor efficiency influenced the traction...
energy consumption of the train. Nowadays, there were relatively few researches on the energy efficiency of URT. In Ref. [5], G H Yu took power and water consumption as input indicators, operation mileage and number of passengers transported as output indicators, and adopted DEA method to measure energy efficiency of URT. In Ref. [6], Wonhwa Hong studied the trend of subway energy efficiency in Korea from 1999 to 2001 in order to analyze how to improve energy efficiency. In Ref. [7], L L Chen believed that big data solution based on Hadoop platform can help improve the energy efficiency management level of subway.

The parametric and non-parametric frontiers methods are often used to evaluate of efficiency. Parameter method needs to determine the specific form of production frontier function, which is difficult to achieve in practical application. However, non-parametric method can overcome this shortcoming, its production frontier function is stochastic, where DEA is the most widely applied. In Ref. [8], Abbas Mardani reviewed 144 articles which published in 45 core journals from 2006 to 2015 and studied energy efficiency based on DEA method, and concluded that DEA method had a good application prospect in energy efficiency research.

Based on above, the paper established an evaluation index system for energy efficiency of urban rail transit with multi-inputs and outputs. Then DEA-BCC model was proposed to evaluate the energy efficiency of URT, and the empirical analysis of Beijing subway Line5, Line15 and Batong Line was carried out to verify its rationality, which aimed to find the influencing factors of energy efficiency of URT from efficiency and slack variable. Last, some suggestions on how to improve energy efficiency of urban rail transit system were given in this paper.

2. Energy efficiency evaluation index system of URT

Introduction

In the paper, energy efficiency of URT was defined as: within specific transportation capacity URT system minimizes the input of electricity energy by making full use of electricity energy and carrying out reasonable energy-saving managements on various power-consuming facilities.

We know 90 percent of the energy consumed by URT is electricity, where traction electricity consumption mainly provides electricity for train operation, L&Ps (lighting and power system) consumption mainly supplies electricity for stations. Therefore, the electricity consumption of train traction and L&Ps were taken as input indexes of the energy consumption of URT.

The main mission of URT is to transport passenger. This paper selected passenger person-kilometres, running kilometrage and passenger volume representing the transport capacity as output indexes. The evaluation index system for energy efficiency of urban rail transit with multi-inputs and outputs was shown as in Table 1.

Table 1. The energy efficiency evaluation index system of URT

| Pointer type | Name of index                   | Index meaning                                                  |
|--------------|---------------------------------|----------------------------------------------------------------|
| Input indexes| Electricity consumption of train traction | -                                                              |
|              | Electricity consumption of L&Ps  | -                                                              |
|              | Passenger person-kilometres     | The sum of passenger travel distances on operating lines during the statistical period. |
| Output indexes| Running kilometrage             | Overall mileages of operating vehicles during the statistical period. |
|              | Passenger volume                | Number of passengers transported during the statistical period. |

3. Methodology

3.1. DEA method

In 1978, A. Charnes and W.W. Cooper et al. proposed DEA method to evaluate the relative validity of ‘departments’ or ‘units’ with multi-inputs and outputs. DEA method has some advantage: firstly, scholars don’t need to select weight coefficient in advance and is not affected by the subjective factors of evaluators; secondly, DEA method does not need to unify the units of input and output data.
Therefore, DEA method is the most widely applied in energy efficiency researches with multi-inputs and outputs.

3.2. BCC model
CCR model can reflect the validity of decision-making units (DMU) under the assumption that the CRS (Constant Returns Scale) unchanged. However, this situation will not last long in practical application. So Banker, Charnes and Cooper proposed BCC model with VRS (Variable Returns Scale).

There are $n$ DMUs, each DMU has $m$ inputs and $r$ outputs. For DMU $j$, the $i$ th input is marked as $x_{ij} = (1,2,...,m)$ and $s$ th output is marked as $y_{sj} = (1,2,...,r)$. In the paper, DMUs are twelve-month, inputs are the electricity consumption of train traction and L&Ps, outputs are passenger person-kilometres, running kilometrage, passenger volume. The data are shown in the table 2.

| Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. |
|------|------|------|------|------|------|------|------|-------|------|------|------|
| $v_1$ | $x_{11}$ | $x_{12}$ | $x_{13}$ | ... | $x_{1m}$ | $y_{11}$ | $y_{12}$ | $y_{13}$ | ... | $y_{1r}$ | $u_1$ |
| $v_2$ | $x_{21}$ | $x_{22}$ | $x_{23}$ | ... | $x_{2m}$ | $y_{21}$ | $y_{22}$ | $y_{23}$ | ... | $y_{2r}$ | $u_2$ |

$v,u$ are the input and output weight vectors, representing the table 2 in matrix form as:

$$x_j = (x_{j1}, x_{j2})^T, y_j = (y_{j1}, y_{j2}, y_{j3})^T, v_i = v^T = (v_1, v_2)^T, u_r = u^T = (u_1, u_2, u_3)^T$$

The efficiency evaluation index $h_j$ is below:

$$h_j = \frac{u^T y_j}{v^T x_j} \leq 1$$

(1)

For DMU $j_0$, the variates are $v_i$ and $u_r$, the evaluation target is $h_{j_0}$, the constraint conditions are $h_j$ of twelve-month. The above conditions can be expressed as:

$$\max \frac{u^T y_j}{v^T x_j} = h_{j_0}$$

s.t. $$\frac{u^T y_j}{v^T x_j} \leq 1, j = 1, \ldots, j_0, \ldots, 12$$

$$v \geq 0, v \neq 0$$

$$u \geq 0, u \neq 0$$

(2)

After dual programmining to formula (2), Archimedes infinitesimal is $\epsilon$, slack variables are $s_i^-, s_j^+$ and weight vectors is $\lambda_j$. The CCR model is as follows:
\[
\min (\theta - e^T s_i + e^T s_i+ ) \\
\sum_{j=1}^{n} \lambda_j x_j + s_i = \theta x_{i0}
\]
\[
\sum_{j=1}^{n} \lambda_j y_j - s_i+ = y_{i0}
\]
Adding constraint condition as formula (4) to CCR model:
\[
\sum_{j=1}^{n} \lambda_j = 1
\]

Then, getting BCC model is as follow:
\[
\min (\delta - e^T s_i + e^T s_i+ ) \\
\sum_{j=1}^{n} \lambda_j x_j + s_i = \delta x_{i0}
\]
\[
\sum_{j=1}^{n} \lambda_j y_j - s_i+ = y_{i0}
\]
\[
\sum_{j=1}^{n} \lambda_j = 1
\]

\[i = 1, 2; r = 1, 2, 3; j = 1, \ldots, 12; 0 < \theta < 1; 0 < \delta < 1; s_i^r \geq 0; s_i^+ \geq 0; e^i = (1, 1), e^+ = (1, 1, 1)\]
\[\theta\] stands for crste, \[\delta\] stands for vrste, scale is \[k = \theta/\delta\]. When \[\theta = 1\] or \[\theta = 1, s_i^r = 0, s_i^+ = 0\] and \[\delta = 1\] or \[\delta = 1, s_i^r = 0, s_i^+ = 0\], the DMU is DEA efficient. Otherwise, the DMU is DEA inefficient.

4. Empirical analysis of Beijing subway
As of December 31, 2017, the mileage of Beijing URT had 684.4 km with the highest passenger flows in the world. The total electricity consumption of Beijing URT is nearly 1.4 billion KWH, and the annual electricity consumption of some lines is about 100 million KWH. This paper compared the energy efficiency of Beijing subway Line 5, Line 15 and Batong Line.

4.1. Efficiency
The efficiency of Beijing subway Line 5, Line 15 and Batong Line were obtained based on BCC model. The paper used radar map to analyze the efficiency of each month of Line 5, Line 15 and Batong Line in 2017. The efficiency situation was shown in figure 1. If crste (technical efficiency from CRS DEA) equals to 1, it meant that the overall energy efficiency of URT was in ideal condition. It also meant that vrste (technical efficiency from VRS DEA) and scale (scale efficiency) were both effective.

![Figure 1. The energy efficiency of subway Line 5, Line 15 and Batong Line in Beijing in 2017](image)
From the mean efficiency and figure 1 (a), it can be seen that crste of Line 15 was the best, followed by Batong Line and Line 5 was the worst. Figure 1 (b) and figure 1 (c) can further reflect the reason why the overall energy efficiency is unsatisfactory because vrste or scale.

Vrste measured whether full use of electrical energy can maximize transport capacity. Scale measured the relationship between electrical energy and transport capacity.

Combined with the data analysis of Line 5, Line 15, and Batong Line, it can be seen that Line 15 had the best overall energy efficiency. For one reason, Line 15 adopted platform screen door compared with Line 5, the platform screen door system can better prevent the loss of air conditioning and heating on the platform, so as to achieve the effect of energy saving. For another reason, compared with Batong Line where platform screen door is also adopted, Line 15’s mean vrste and scale were higher, which indicated that Line 15 make better use of electric energy, and the input-output ratio between electricity energy and transportation capacity was more reasonable. The overall energy efficiency of Batong Line was more ideal than that of Beijing subway Line 5, one of the reasons was that Batong Line has no underground station, so the electricity consumption of L&Ps can be better controlled in summer.

4.2. Slack variable analysis

Through analyzing slack variables, it can provide improvement and adjustment direction to the month with low energy efficiency. In this paper, specific value was hidden, and indicators with input redundancy or output shortage were only marked with a tick, and the slack variables were plotted as shown in table 3. The electricity consumption of train traction had no redundancy, running kilometrage’s output shortage was rare. However, most of the redundancy concentrated on electricity consumption of L&Ps, output shortage concentrated on passenger person-kilometers and passenger volume. In February, March and August, there were no input redundancy and output shortage.

It can be found that in January due to Spring Festival the decrease of the passenger volume resulted in the redundant input and output shortage. In February, passenger volume increased again, the redundant input and output shortage disappeared, but the energy efficiency didn’t reach optimal level. In March during Two Sessions, the trip of public transportation and private cars were regulated, the number of passengers in the three subway lines increased sharply, so that the energy efficiency reached optimal level. In August, there was no input redundancy and output shortage and vrste was 1, which showed that URT enterprises made better use of electric energy in August than in June or July. It can be found passenger person-kilometers in August was higher than in June and July, people traveled longer distances during summer holidays which improved the energy efficiency of URT.

Table 3. Slack variables of Beijing subway Line 5, Line 15 and Batong Line in 2017

| Indexes | Redundant input | Output shortage |
|---------|-----------------|-----------------|
| Line    | Electric consum-| Passenger person-| Running |
|         | traction       | -tion of L&Ps   | kilometre |
|         | 5 15 Batong 5  | 15 Batong 5 15  | 5 15 Batong 5 15 |
| Jan.    | √              | √               | √           |
| Feb.    |                |                 |             |
| Mar.    |                |                 |             |
| Apr.    | √              | √               | √           |
| May.    | √              | √               | √           |
| Jun.    | √              | √               | √           |
| Jul.    | √              | √               | √           |
| Aug.    |                |                 |             |
| Sept.   |                |                 |             |
| Oct.    |                |                 |             |
5. Conclusion and Suggestions

From the perspective of economics, the paper established an evaluation index system for energy efficiency of URT with multi-inputs and outputs. Then DEA-BCC model was proposed to evaluate the energy efficiency of urban rail transit, and the empirical analysis of Beijing subway Line5, Line15 and Batong Line was carried out to verify its rationality. The results showed that energy efficiency of URT was related to three factors, including platform equipments, station type and passengers and the operation mileage successively. Particularly in June and August, the impacts of platform equipments system and station type on the energy efficiency of subway were more significant, and some suggestions for URT corporation were given, such as adopting platform screen door system and attracting more passengers.

Acknowledgments

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