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EFFICIENCY OF PUBLIC TRANSPORT OPERATIONS: A COMPREHENSIVE EVALUATION APPROACH IN CHINA CITY

Xiaoyan Wu[1], Danping Dong[1], Xueshi Ma[2], Wenjian Zheng[1], Xin Li[1] & Fulu Wei*[1]
[1]School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo 255000, Shandong, China
[2]Traffic Management Division, Gaoxin Traffic Police Detachment of Zibo Public Security Bureau, Zibo, Shandong, 255000, China

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ABSTRACT

To overcome the problem of single evaluation index in the existing public transport operation efficiency evaluation system, the analytic hierarchy process (AHP) and fuzzy evaluation (FE) methods were integrated to build a public transport operation efficiency index evaluation system that includes rationality, convenience, and comfort as the criteria layer and seven key elements as the core indicator layer. Based on multi-level comprehensive evaluation, a public transport operation efficiency analysis model and classification table were established. The results of case study showed that the comprehensive evaluation index values of the three bus lines are No. 39 at 5.97, No. 40 at 7.33, and No. 41 at 3.62, which can be used to judge the operation status of public transport directly and to select the optimal bus line design quickly.

KEYWORDS: Bus line; Operation efficiency; Analytic Hierarchy Process; Comprehensive evaluation.

1. INTRODUCTION

The rapid development of the economy is accelerating the process of urbanization in China. The improvement of living standards has increased the number of private cars. Thus, the demand for transportation is increasing, which brings more and more pressure on the urban traffic supply [1-4]. The imbalance of traffic supply and demand causes increased prominence of contradictions related to traffic congestion, environmental pollution, and commuting difficulties [5-6]. Urban congestion must be addressed, and the advantages of public transport are becoming more prominent. Public transport has large passenger capacity, efficiently uses urban land, lowers travel cost for residents, provides low-carbon environmental protection, etc., which can effectively alleviate urban traffic pressures [7-10] and in recent years the state has paid increasing attention to public transport, whose status is increasing, development trends are good, and the function of traffic dispersion is more and more obvious.

Therefore, the operation efficiency and service level of public transport need to be improved. Only by increasing competitiveness can private car travel be effectively reduced and traffic congestion alleviated. This demands higher requirements for the operation efficiency of public transport. It is urgent to carry out quantitative and qualitative analyses on the operation efficiency of public transport to meet the travel needs of urban residents.

In summary, existing methods select primarily relevant evaluation indexes from the aspects of public transport that include service level, public transport operation reliability, public transport operation efficiency, etc., to establish an evaluation model. However, less consideration is given to the relevance of public transport operation indexes, which can lead to evaluation results that are not comprehensive and objective, and the evaluation of the overall operation of public transport lacks systematic research. In this study, several key technical indicators that greatly impact the operation of public transport were selected, and a multi-level comprehensive evaluation on the operation efficiency of public transport from the aspects of rationality, convenience, and comfort was conducted. Buses 39, 40, and 41 of Pingdingshan City were used as examples to evaluate the current operation efficiency of public transport.

2. CONSTRUCTION OF EVALUATION INDEX SYSTEM

The construction of an evaluation index system should select relevant parameters that can represent the characteristics of urban traffic operation and reflect the system comprehensively and systematically. The selection of indicators should follow the basic principles of systematization, comprehensiveness, technicality, and enforceability. In view of this, this study used rationality, convenience, and comfort as the criteria layer and selected seven technical indicators—line length, non-linear coefficient, station spacing, multiple line coefficient, departure interval, number of vehicles allocated, and operating speed—to build a public transport operation efficiency evaluation system. A detailed analysis is as follows.

2.1. Rationality evaluation index

(1) Line length is the total length(*s*) of the actual operation line of public transport. There are certain requirements and standards for line length specifications, and line ranges in different urban and regional are different. For example, there are provisions in urban road traffic planning and design specifications; the length of the main bus lines located in an urban area is appropriate to be 8–12km, and the length of the bus lines is related to urban scale, urban form, average riding distance of urban residents, and other factors. For small and medium-size cities, the lower limit can be appropriately relaxed; the upper limit can be appropriately relaxed for mega cities and belt cities. Bus lines that are too long will lead to unbalanced passenger flow distribution, difficult coordination of departure frequency, and low efficiency of bus line.

(2) Nonlinear coefficient is the ratio of the actual operation length (*S*) of the public transport line to the space straight-line distance (*L*), i.e., *S/L*. According the Code for Planning and Design of Urban Road Traffic (GB 50220-95), the non-linear coefficient of public transport lines should not be too large. If the line is too long, the service scope of the line will be expanded, and the additional journey and travel time of passengers will be increased accordingly. However, short lines will also cause waste of bus resources and cannot meet the travel needs of passengers well. Generally, the non-linear coefficient should be greater than 1.1. According to GB 50220-95, the non-linear coefficient of public transport lines must not be greater than 1.4, and the average non-linear coefficient of the whole line network must be 1.1–1.4.

2.2. Convenience evaluation index

(1) Multiple line coefficient refers to the number of bus lines served by a station. Considering the uniformity of bus line distribution, station coverage, passenger flow sharing rate of each line at stations, station parking capacity, etc., the multiple line coefficient of a road is generally not more than 3–5, and the main road should not be more than 8.

(2) Running speed is the use of the ratio of travel distance (*S*) and travel time (*t*) of the bus line, i.e., (*S/t*). When selecting the public transport mode, its operation speed must be adapted to the passenger flow on the line. The common operation speed of public transport mode is shown in Table 1.

Table 1. Operation speed of public transport mode

Public transport mode	Speed (km/h)	Departure frequency (Train number/h)	One way passenger capacity (Thousands of people/h)
Bus	16-25	60-90	8-12
Trolleybus	15-20	50-60	8-10
Tram	14-18	40-60	10-15

2.3. Comfort evaluation index

There is a relationship between the comfort of passengers, departure intervals, and the number of buses. When the departure interval is long, the waiting time of passengers at the platform will be prolonged, and the number of passengers on the bus will usually be more and crowded. The waiting time will be long, which will reduce the comfort of passengers and increase the sense of annoyance of passengers. Therefore, a proper departure interval can give passengers a good sense of comfort. Departure intervals need to have a reasonable number of vehicles, otherwise the system cannot meet its requirements.

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Vehicles start from the origination station and return to it after running to its terminating station, called a turnover. The calculation formula for the number of vehicles allocated in the period is expressed as Eq. 1:

$$P_i = \frac{H_i}{\rho_i C} \tag{1}$$

where P_i is the number of vehicles allocated in the *i* period (vehicle); H_i represents the maximum passenger flow during the *i* period (person); *C* is the vehicle capacity (person); ρ_i is the expected full load rate in the *i* period; and the full load rating is generally 0.8–1.1 at the peak hour and 0.5–0.6 at the flat peak.
The departure interval in peak hours t_{int} is expressed as Eq. 2.

$$t_{\text{int}} = \frac{60}{P_m} \tag{2}$$

3. FUSION MODELING OF AHP AND FUZZY EVALUATION

The operation of public transport lines was evaluated and analyzed, and the following comprehensive evaluation model was established by combining AHP with fuzzy evaluation methods [11-15], as shown in Eq. 3 and Eq. 4.

$$SI=\sum b_i \times B_i \text{ , } (i=1, 2, 3) \tag{3}$$

$$B_i=\sum a_i \times C_i \text{ , } (i=1, 2, 3, 4, 5, 6, 7) \tag{4}$$

where *SI* represents the comprehensive index of conventional public transport operation evaluation; B_i represents the fuzzy quantitative value of each evaluation index in criterion level; b_i is the evaluation index weight vector of criteria level; C_i represents the fuzzy quantitative value of core index layer; and a_i is the core index weight vector. The weight calculation steps are as follows. (1) Multiply the row vectors to the nth power and get the values of each row in turn to get the relative weight, which is calculated by Eq. 5.

$$L_i=\sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{5}$$

(2) Normalize the weight vector of the column matrix composed of *L*, as shown in Eq. 6.

$$T_i=L_i \Big/ \sum_{i=1}^{n} L_i \tag{6}$$

where T_i is the weight of level *i*.

(3) Conduct a consistency test. First, the maximum eigenvalue is calculated, and the consistency index can be further calculated based on the maximum eigenvalue. Finally, the index ratio between the judgment consistency index and the average random consistency index is calculated to obtain the test consistency index. The calculated Eq. 7, Eq. 8, and Eq. 9 are expressed as follows.

$$\lambda_{max}=\frac{1}{n}\sum_{i=1}^{n}\frac{(AL)_i}{L_i} \text{, thus } A\cdot\omega=\lambda_{max}\cdot\omega \tag{7}$$

$$CI=\frac{\lambda_{max}-n}{n-1} \tag{8}$$

$$CR=\frac{CI}{RI} \tag{9}$$

where λ_{max} is maximum eigenvalue; *CI* and *CR* represent the indexes of judging the consistency.

4. CASE ANALYSIS

Based on the investigation of buses 39, 40, and 41 in Pingdingshan City, data were obtained by sorting and analyzing. According the evaluation model, the corresponding data was selected for the criteria layer and the core indicator layer.

The fuzzy quantification of rationality index and weight calculation are shown in Table 2.

Table 2. Fuzzy quantization of rationality indicators.

Quantized value	Line length C_1	Non-linear coefficient C_2	Station spacing C_3	Rationality
1	(0, 6]	(1.5, 1.8]	(1000, 1100]	Extremely unreasonable
3	(6, 8]	(1.0, 1.1]	(800, 1000]	Unreasonable
5	(14, 16]	(1.4, 1.5]	(600, 800]	General
7	(12, 14]	(1.1, 1.2]	(0, 400]	Reasonable
9	(8, 12]	(1.2, 1.4]	(400, 600]	Extremely unreasonable

The index weight calculation is shown in Eq. 10.

$$A\cdot\omega=\begin{pmatrix}1 & 2 & 3\\ 1/2 & 1 & 2\\ 1/3 & 1/2 & 1\end{pmatrix}\begin{pmatrix}0.540\\ 0.297\\ 0.163\end{pmatrix}=\begin{pmatrix}1.623\\ 0.893\\ 0.492\end{pmatrix} \quad (10)$$

The expression of the maximum eigenvalue(λ_{max})is calculated as Eq. 11.

$$\lambda_{max}=\frac{1}{3}\left(\frac{1.623}{0.540}+\frac{0.893}{0.297}+\frac{0.492}{0.163}\right)=3.0092 \quad (11)$$

When n=3, the CI value can be calculated as Eq. 12.

$$CI=\frac{\lambda_{max}-n}{n-1}=\frac{3.0092-3}{3-1}=0.0046 \quad (12)$$

At this time, the average random consistency index RI = 0.58, then the CR value can be calculated as: $CR=\frac{CI}{RI}=\frac{0.0046}{0.58}=0.0079<0.1$.

Therefore, A has passed the consistency test, and the weight vector of C_1, C_2, C_3 is a_i = {0.540, 0.297, 0.163}, B_i =0.540 C_1+0.297 C_2+0.163 C_3.
The weight calculation of index C_4, C_5 is expressed as follows:

As known matrix $A=\begin{pmatrix}1 & 1/2\\ 2 & 1\end{pmatrix}$, the weight vector of C_4, C_5 is calculated as a_j = {0.333, 0.667}, B_2 = 0.333 C_4+0.667 C_5.
Fuzzy quantification and weight calculation of comfort index are shown in Table 3.

Table 3. Fuzzy quantitative values of comfort indicators.

Quantized value	Number of vehicles C_6	Running speed C_7	Comfort
1	(0, 10]	(0, 10]	Extremely uncomfortable
3	(10, 15]	(10, 15]	Uncomfortable
5	(15, 20]	(15, 20]	General
7	(20, 25]	(20, 25]	Comfortable
9	(25, 30]	(25, 30]	More comfortable

The weight calculation of index C_6, C_7 is expressed as follows:
As known matrix $A=\begin{pmatrix}1 & 1/3\\ 3 & 1\end{pmatrix}$, the weight vector of C_6, C_7 is calculated as a_k = {0.250, 0.750}, B_3 = 0.25 C_6+0.75 C_7.

Calculation of weight vector of criterion layer. Judgment matrix $A=\begin{pmatrix}1 & 4/3 & 2\\ 3/4 & 1 & 2\\ 1/2 & 1/2 & 1\end{pmatrix}$. The relative weights are calculated as $\sqrt[3]{1\times4/3\times2}=1.387$, $\sqrt[3]{3/4\times1\times2}=1.145$, $\sqrt[3]{1/2\times1/2\times1}=0.630$, and $1.387+1.145+0.630=3.162$. Standardize the

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weight vector; its value is $1.387/3.162=0.438$, $1.145/3.162=0.362$, $0.630/3.162=0.200$. Thus, Eq. 13 can be expressed as follows.

$$A{\cdot}\omega=\begin{pmatrix} 1 & 4/3 & 2 \\ 3/4 & 1 & 2 \\ 1/2 & 1/2 & 1 \end{pmatrix}\begin{pmatrix} 0.438 \\ 0.362 \\ 0.200 \end{pmatrix}=\begin{pmatrix} 1.321 \\ 1.091 \\ 0.600 \end{pmatrix} \quad (13)$$

Maximum eigenvalue $\lambda_{max}=\frac{1}{3}\left(\frac{1.321}{0.438}+\frac{1.091}{0.362}+\frac{0.600}{0.200}\right)=3.0099$ and $CI=\frac{\lambda_{max}-n}{n-1}=\frac{3.0099-3}{3-1}=0.00495$, when n=3, average random consistency index RI=0.58, $CR=\frac{CI}{RI}=\frac{0.00495}{0.58}=0.0085<0.1$. Therefore, A passed the consistency test, and the weight vectors of B_1, B_2, B_3 are calculated as $b_i=\{b_1 \quad b_2 \quad b_3\}=\{0.438 \quad 0.362 \quad 0.200\}$, SI=0.438 B_1+0.362 B_2+0.200 B_3.

According to the comprehensive evaluation model established above, relevant indicators are calculated and the calibration results of the comprehensive evaluation model for the operation status of conventional public transport are obtained, as shown in Eqs.14–17.

$$SI=0.438\,B_1+0.362\,B_2+0.200\,B_3 \quad (14)$$
$$B_1=0.540\,C_1+0.279\,C_2+0.200\,C_3 \quad (15)$$
$$B_2=0.333\,C_4+0.667\,C_5 \quad (16)$$
$$B_3=0.250\,C_6+0.750\,C_7 \quad (17)$$

To evaluate operation efficiency, bus line data for 39, 40, and 41 of Pingdingshan City were investigated. Through direct or indirect calculation, the line length C_1, non-linear coefficient C_2, distance between stations C_3, multiple line coefficient C_4, departure interval C_5, number of vehicles C_6, and speed C_7 were obtained, as shown in Table 4.

Table 4. Basic information on current status of public transport.

Line	Bus 39	Bus 40	Bus 41
Line length	15.9 km	11.9 km	18.10 km
Number of sites	29	24	28
Straight line distance	13.3 km	9.2 km	6.7 km
Average running time	50 min	40 min	50 min
Average distance between stations	567.86 m	507.69 m	646.43 m
Non-linear coefficient	1.195	1.348	2.567
Running speed	19.08 km/h	18.6 km/h	22.9 km/h
Average double coefficient	9	9	5
Departure interval	7-8 min	9 min	20/25 min
Number of vehicles	18 vehicles	14/16 vehicles	9/10 vehicles

From Table 5, we can intuitively understand the current situation of public transport operation. According to the seven key evaluation indicators, the evaluation results obtained are objective, comprehensive, and credible.

Table 5. Evaluation results of current status of public transport operation.

Line	*SI*	Range	Evaluation	Health description
Bus 39	5.97	(4, 6]	General	Smooth operation, acceptable passengers, moderate comfort.
Bus 40	7.33	(6, 8]	Better	Smooth operation, better convenience, more comfortable passengers.
Bus 41	3.618	(2, 4]	Poor	Poor convenience, passengers a little irritable.

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As shown in Table 5, bus 39 is set reasonably, but the convenience of bus stops and passenger comfort could be further improved. The comprehensive evaluation of bus 40 is good, and the route design is reasonable, convenient, and comfortable. The layout of bus 41 is not reasonable; convenience needs to be further improved, and the comfort level of passengers is low.

It can be seen that the method established in this study can reflect the current situation of bus line operation intuitively and objectively and can identify the shortcomings of the current situation of bus operation. Thus, it can provide targeted solutions and a theoretical basis for public transport operation management.

5. CONCLUSIONS

In this study, the AHP and fuzzy evaluation methods were combined to build a comprehensive evaluation model, and the three criteria levels of rationality, convenience, and comfort were set up. Seven technical indicators were selected, including line length, non-linear coefficient, distance between stations, multiple line coefficient, departure interval, number of vehicles allocated, and running speed. The service level and efficiency of public transport operation were comprehensively analyzed and graded.

The data in this research was distracted from Pingdingshan, China. Whether the evaluation method proposed in this paper has satisfactory transferability remains to be verified. In the future, more city bus data will be extracted to explore the transferability of the evaluation method.

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