Research on Evaluation of Urban Rail Transit Service Level

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Abstract: Evaluating the level of urban rail transit services objectively is of great significance to improving its operational efficiency. This paper analyzes and constructs the urban rail transit service level index system from the perspective of passengers, and proposes a comprehensive evaluation model of service level based on Set pair analysis. Through the calculation of weights and connections, analysis of each impact indicator is carried out from four levels. Taking Wuxi Metro Line 1 as an example, this model was used to evaluate its service level comprehensively. The example verification shows that the service level of Wuxi Metro Line 1 is relatively high. The application of the model can comprehensively evaluate the service level of urban rail transit, and can reflect the limiting factors affecting the service level. It provides theoretical support for the development of urban rail transit operations.

1. Introduction
As a new type of transportation, urban rail transit attracts a large number of passengers with its fast, comfortable and safe performance. With the improvement of residents' living standards, passengers pay more attention to the quality of public transportation services. From the perspective of long-term planning and operation development of rail transit construction, the optimization of urban rail transit service level is of great significance.

At present, the domestic research on the urban rail transit service level is still in its infancy, mainly from the index system construction and evaluation level analysis for verification. The literature [1] is mainly developed from stations, trains, lines and networks and uses 12 evaluation indicators as carriers. Finally, the indicators are quantified and graded to determine the level of urban rail transit service levels. The literature [2] is mainly based on the station hall, platform and train construction, and establishes an evaluation system from the aspects of safety, convenience, comfort and economy, and applies the analytic hierarchy process for comprehensive evaluation. Literature [3] proposed to establish a comprehensive evaluation model of urban rail transit service level based on attribute recognition theory, and the confidence criterion used to identify urban rail transit service level. In [4], based on the definition of the passenger flow state of urban rail transit operations, and the evaluation system is established from the gates, passages and stairs. Literature [5] analyzes and establishes an indicator system from pre-trip information, road information, station information and train information.
from the perspective of travellers. Literature [6] mainly proposes quantitative indicators from the perspective of urban rail transit and public exchange, and uses the fuzzy comprehensive evaluation method to establish a quantitative evaluation model for bus and subway transfer. Literature [7] mainly evaluates service levels through scoring in the form of passenger satisfaction survey, which is subjective and cannot objectively reflect the characteristics of rail transit operations. Literature [8] establishes a comprehensive evaluation model for pedestrian flow-density, and the evaluation index is relatively simple. In [9], the SEM structural equation model is used in rail transit to clearly analyze the impact of individual indicators on the overall and the correlation between individual indicators.

In summary, aiming at the subjective problem of evaluation index and evaluation method in urban rail transit, this paper proposes qualitative and quantitative comprehensive analysis of 14 evaluation indicators based on safety, convenience, comfort and economy. The set-level analysis method is used to establish the service level evaluation model, and the Wuxi Metro Line 1 is taken as an example to verify the theory.

2. Urban rail transit service level evaluation model

2.1 Urban Rail Transit Service Level Evaluation System

Based on the reference literature and the study of foreign urban rail transit service level, this paper combines the characteristics of domestic urban rail transit development, and investigates urban rail transit systems such as Hangzhou, Wuxi, Suzhou and Nanjing. Finally, establish evaluation system with safety, convenience, comfort and economy as the carrier. (Table 1).

(1) Safety indicators. Safety is the first choice for passengers to choose transportation. It mainly analyzes urban rail transit from the aspects of security inspection and safety equipment.

(2) Convenience indicators. This type of indicator mainly describes the passengers' satisfaction with the accuracy, timeliness and convenience of the information provided by the subway. Mainly from the passenger transfer and timeliness, select the departure interval, operation time, travel speed, punctuality rate, walking distance and convenience of ticketing for quantitative and qualitative analysis.

(3) Comfort indicators. This type of indicator mainly reflects the comfort level of passengers taking the subway. Quantitative analysis is mainly carried out from the density of the seats, the noise level inside the car and the rate of change of the acceleration and deceleration.

(4) Economic indicators. This indicator reflects passengers' emphasis on time value and economic carrying capacity. Quantitative and qualitative analysis is mainly based on fare rationality, time value ratio and network coverage.

Table 1. Urban Rail Transit Service Level Evaluation Index System

| Criteria layer | Evaluation index | Evaluation parameter | Evaluation level (j) |
|----------------|------------------|----------------------|---------------------|
|                |                  |                      | Higher (S₁) | High (S₂) | Medium (S₃) | Low (S₄) |
| Safety         | I₁               | Security inspection  | [10,8]         | [8,6]     | [6,3]       | [0,3]     |
|                | I₂               | Safety facilities    | [10,8]         | [8,6]     | [6,3]       | [0,3]     |
| Convenience    | I₃               | Departure interval / min | [0,4]         | [4,8]     | [8,12]      | [12,20]   |
|                | I₄               | Operating time / h   | [20,24]        | [16,20]   | [13,16]     | [0,13]    |
|                | I₅               | Travel speed / (km·h⁻¹) | [50,80]      | [35,50]   | [25,35]     | [20,70]   |
|                | I₆               | Punctuality rate /%  | [100,90]       | [90,80]   | [80,70]     | [70,0]    |
|                | I₇               | Walking distance /m  | [0,500]        | [500,800] | [800,1200]  | [1200,2000] |
|                | I₈               | Convenience in purchasing tickets | [10,8] | [8,6] | [6,3] | [0,3] |
| Comfort        | I₉               | Standing density / (peoples·m⁻²) | [0,2] | [2,4] | [4,6] | [6,10] |
|                | I₁₀              | In-vehicle noise level /dB | [60,65] | [65,70] | [70,75] | [75,80] |
|                | I₁₁              | Acceleration and deceleration rate / (m·s⁻²) | [1,2,1.5] | [0,9,1.2] | [0,7,0.9] | [0,5,0.7] |
This paper mainly draws on the division method of TCRP public transportation service level in the service level index system classification and threshold determination. The level of urban rail transit service is graded from "higher, high, medium and low". The determination of the threshold value in the evaluation system is mainly based on the experience and objective evaluation of the subway experts in each city.

2.2 Urban Rail Transit Service Level Evaluation Method

2.2.1 Set Pair Analysis Theory. This paper uses the set pair analysis method to establish a comprehensive evaluation model of urban rail transit service level. Set pair analysis is a "wide-area" mathematical analysis method that covers the concept of "degree of contact". The method can eliminate the subjective factors, effectively determine the level of urban rail transit service level and the difference between the indicators, and provide a theoretical basis for the evaluation of urban rail transit service level.

Set pair analysis usually analyzes from the perspective of set, transforms the uncertainty problem into two sets and quantifies the index, and finally draws the "same, different, opposite" relationship between the two sets in the context of uncertain problems.

\[ \mu = a + bi + cj \quad (1) \]

In the calculation, \( \mu \) indicates the degree of contact; \( a, b, c \) indicates the same, the difference, and opposition; \( i, j \) indicates the difference coefficient, the opposite coefficient. Formula meets normalization conditions: \( a + b + c = 1 \). \( i \) change between [-1, 1], representing problems between determinism and uncertainty, \( j \) take -1 and 1, the questions expressed are all deterministic.

2.2.2 Connection calculation. The core idea of the connection degree calculation is: the degree of connection is 1, which means that the evaluated indicators are within the level range, indicating a unified relationship; the degree of contact is -1, indicating that the evaluated indicators are not in the unified evaluation level, which is an opposite relationship. When the evaluated indicator is between the two, it can be calculated by the following formula:

Evaluation indicators are at the "low" level:

\[ \mu_{11} = \begin{cases} 
1, & x \in [S_{i(0)}, S_{i(1)}] \\
1 + \frac{2(x - S_{i(1)})}{S_{i(1)} - S_{i(2)}}, & x \in [S_{i(1)}, S_{i(2)}] \\
1, & x \in [S_{i(2)}, +\infty]
\end{cases} \quad (2) \]

Evaluation indicators are at the "medium" level:

\[ \mu_{12} = \begin{cases} 
1 + \frac{2(x - S_{i(1)})}{S_{i(1)} - S_{i(0)}}, & x \in [S_{i(0)}, S_{i(1)}] \\
1, & x \in [S_{i(1)}, S_{i(2)}] \\
1 + \frac{2(x - S_{i(1)})}{S_{i(2)} - S_{i(0)}}, & x \in [S_{i(2)}, S_{i(3)}] \\
1, & x \in [S_{i(3)}, +\infty]
\end{cases} \quad (3) \]

Evaluation indicators are at the "high" level:
Evaluation indicators are at the "higher" level:

\[
\mu_{ij} = \begin{cases} 
\frac{1}{1+\frac{2(x-S_{i(i)})}{S_{i(i)}-S_{i(2)}}} & x \in \left[ S_{i(3)}, S_{i(4)} \right] \\
\frac{2(x-S_{i(2)})}{S_{i(3)}-S_{i(1)}} & x \in \left[ S_{i(0)}, S_{i(3)} \right] \\
-1 & x \in \left[ S_{i(1)}, S_{i(2)} \right] 
\end{cases}
\]  

(4)

Formula(2)~(5), \(x\) indicates the lower limit of each evaluation indicator; \(S_{ij}\) indicates the measured value of the evaluation index; \(S_{ij}\), \(S_{ij}\), \(S_{ij}\), \(S_{ij}\) representing the limits of each evaluation indicator level, \(\mu_{ij}\) indicates the degree of connection of the evaluation indicators to the standards of each evaluation level respectively. After calculating the contact degree of each indicator by the above method, the total contact degree is calculated using equation (6).

\[
\mu_j = \sum_{i=1}^{m} \mu_{ij} \cdot \omega_j
\]  

(6)

Formula(6), \(\mu_j\) indicates the total contact level of each evaluation indicator for the level \(j\); \(\omega_j\) indicates the weight value of the \(j\)th level corresponding to the \(i\)th indicator. The maximum value of the contact degree represents the evaluation level of an urban rail transit service level.

2.2.3 Determination of indicator weight.

The indicator weight value represents the degree of importance between the indicators. The index over-standard method objectively reflects the degree of exceeding the standard of each indicator. The basic idea is: first calculate the weight of each level corresponding to each index by using equation (7), and then normalize it with equation (8).

\[
P_{ij} = \frac{I_{ij}}{I_{ij}}
\]  

(7)

\[
\omega_j = \frac{P_{ij}}{\sum_{i=1}^{m} P_{ij}}
\]  

(8)

Formula(7)~(8), \(P_{ij}\) indicates the index of each indicator \(i\) corresponding to level \(j\); \(I_{ij}\) indicates the magnitude of the evaluation indicator \(i\); \(I_{ij}\) indicates the standard median of the corresponding level \(j\) of indicator \(i\). \(P_{ij}\) indicates the extent to which each evaluation indicator exceeds the standard value of the level.

3. Instance application

Take Wuxi Metro Line 1 as an example, and apply the pair analysis method to comprehensively evaluate its service level.

(1) The data collection in this paper is mainly divided into 2 parts. The results of the survey statistics are listed in Table 2.

Collect relevant quantitative data from Wuxi Metro Operation Company, including departure interval (\(C_3\)), operation time (\(C_4\)), travel speed (\(C_5\)), punctuality rate (\(C_6\)), walking distance (\(C_7\)), seat
density (C9), and interior noise level (C10), acceleration/deceleration rate (C11), time-to-value ratio (C13).

Relevant qualitative data were obtained through field surveys and questionnaires, including security (C1), equipment for safety facilities (C2), convenience of ticketing (C8), reasonable fare (C12), and network coverage (C14).

### Table 2. Evaluation values of evaluation indicators (Cj)

| Evaluation index | Measured value | Evaluation index | Measured value |
|------------------|---------------|------------------|---------------|
| C1               | 9             | C8               | 7             |
| C2               | 8.5           | C9               | 1.45          |
| C3               | 4.75          | C10              | 65.3          |
| C4               | 16.5          | C11              | 1.00          |
| C5               | 35.3          | C12              | 8             |
| C6               | 95.5          | C13              | 0.38          |
| C7               | 815.6         | C14              | 7.9           |

(2) The normalized weight values of each evaluation index are calculated using equations (7) and (8), as shown in Table 3.

### Table 3. Normalized weights for each level of evaluation indicators (%)

| Evaluation index | Higher (S1) | High (S2) | Medium (S3) | Low (S4) |
|------------------|-------------|-----------|-------------|----------|
| C1               | 0.10        | 0.13      | 0.19        | 0.58     |
| C2               | 0.10        | 0.13      | 0.19        | 0.58     |
| C3               | 0.60        | 0.20      | 0.12        | 0.08     |
| C4               | 0.14        | 0.19      | 0.21        | 0.47     |
| C5               | 0.54        | 0.15      | 0.22        | 0.52     |
| C6               | 0.17        | 0.18      | 0.21        | 0.44     |
| C7               | 0.56        | 0.21      | 0.14        | 0.09     |

(3) Calculate the contact degree of each evaluation index level according to formulas (2) ~ (5), and obtain the degree of contact of the indicator from service level index system index layer C. The evaluation results are shown in Table 4.

### Table 4. Contact degree of urban rail transit service level evaluation index

| Criteria layer B | Evaluation index | Evaluation parameter | Evaluation level (j) |
|------------------|------------------|----------------------|----------------------|
| Safety           | B1               | I1 Safety inspection | Higher (S1)         |
|                  |                  |                      | High (S2)           |
|                  |                  |                      | Medium (S3)         |
|                  |                  |                      | Low (S4)            |
| Convenience      | B2               | I5 Departure interval | -0.225              |
|                  |                  |                      | 0.2                 |
|                  |                  |                      | -0.075              |
|                  |                  |                      | -0.08               |
|                  | I4 Operating time | -0.105               |
|                  |                   |                      | 0.19                |
|                  |                   |                      | 0.16                |
|                  | I5 Travel speed   | 0.5                  |
|                  |                   |                      | 0.15                |
|                  |                   |                      | 0.21                |
|                  |                   |                      | -0.52               |
|                  | I6 Punctuality    | -0.17                |
|                  | rate (%)          |                      | -0.018              |
|                  |                   |                      | -0.21               |
|                  |                   |                      | -0.44               |
|                  | I7 Walking distance | -0.56              |
|                  |                   |                      | 0.23                |
|                  |                   |                      | 0.14                |
|                  |                   |                      | -0.08               |
|                  | I8 Convenience in | 0                    |
|                  | purchasing tickets|                      | 0.13                |
|                  |                   |                      | 0                   |
|                  |                   |                      | -0.58               |
| Comfort          | B3               | I9 Standing density  | 0.43                |
|                  |                  |                      | 0.13                |
|                  |                  |                      | -0.17               |
|                  |                  |                      | -0.11               |
|                  | I10 In-vehicle    | 0.25                 |
|                  | noise level /dB   |                      | 0.26                |
|                  |                   |                      | -0.21               |
|                  |                   |                      | -0.22               |
|                  | I11 Acceleration  | 0.11                 |
|                  | and deceleration  |                      | 0.21                |
|                  | rate /dB          |                      | 0.14                |
|                  |                   |                      | -0.36               |
(4) Calculate the total connection degree of the criteria layer B in the service level indicator system according to the formula (6): safety, convenience, comfort, economy. Obtain the total contact degree of the service level A, as shown in Table 5.

Table 5. Total contact degree of service level evaluation indicators

| Evaluation object | Evaluation level (j) | Higher (S1) | High (S2) | Medium (S3) | Low (S4) |
|-------------------|----------------------|-------------|-----------|-------------|---------|
| Safety B1         |                      | 0.2         | 0.065     | -0.38       | -1.16   |
| Convenience       |                      | -0.56       | 0.882     | 0.225       | -2.17   |
| Comfort B3        |                      | 0.79        | 0.6       | -0.24       | -0.69   |
| Economic B4       |                      | 1.5         | 0.35      | -0.48       | -1.25   |
| Service Level A   |                      | 1.73        | 1.832     | -0.72       | -1.94   |

It can be seen from the evaluation results of Tables 5 and 6 that the service level of Wuxi Metro Line 1 is generally “high”. In the criteria layer, the rating levels of safety, comfort, and economy are “higher”, and the rating level of convenience is “high”. In the evaluation system index layer, security inspection, safety facilities and equipment, travel speed, seat density, time value ratio, and network coverage evaluation level are “higher”. The departure interval, operating time, on-time rate, walking distance, convenience of ticket purchase, noise level in the car, rate of change in acceleration and deceleration, and evaluation level of fare reasonableness are “high”. Thus, the convenience in subway needs to be improved for meeting the needs of passengers.

4. In conclusion

This paper selects four carriers of safety, convenience, comfort and economy in the construction of urban rail transit service level index system, and 14 indicators analyzed uses the set pair analysis method. The model not only objectively evaluates service level levels, but also effectively reflects the limiting factors that affect service levels.

Taking Wuxi Metro Line 1 as an example, the model proposed in this paper is used for comprehensive verification. The results show that the service level of Wuxi Metro Line 1 is “high”, and the main limiting factors are reflected in the convenience. The conclusions drawn by the model are consistent with the actual situation in Wuxi, indicating its practicability.

In the establishment of the index system, there is a lack of method screening for the selection of indicators. Some indicators lack quantitative treatment due to the constraints of the survey conditions, which will be the focus of further research in future research.

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