

# Multidimensional Coefficient Approach to Comfort Evaluating for High-speed Train

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## Abstract

*In the complex operation environment of high-speed trains, the comprehensive evaluation index systems with high scientificity and measurability have been established after the all-round analysis of various effects on comfort for high-speed train. Meanwhile, a comprehensive evaluation method on comfort for high-speed train has been built by the rough set theory and multidimensional coefficient theory. The real examples have shown that the evaluating process is scientific, intuitive and convenient.*

**Keywords:** rough set, multidimensional coefficient, high-speed train, comfort evaluating

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## 1. Introduction

With the increasingly rapid development of high-speed trains and during the localization process of operation technologies for high-speed trains in China, The research on comfort for high-speed trains is more important in our days than it on improved manufacturing, criterion of equipment and process and operation management. After the quantitative and systemic analysis of comfort for passenger riding, the mathematical model of comfort for high-speed trains, including the specific analysis, evaluation and prediction, has been built by the method of multivariate analysis, which can provide more comprehensive scientific methods and reference for the design and manufacture of high-speed trains in China [1].

Currently, the research on comfort evaluating for passenger on board mainly focus on several dominant factors, including body vibration, noise. Many domestic scholars have built the evaluation methods and index of comfort for tilting trains and proposed the corresponding evaluation criterion of comfort when vibration exists, after the learning and research of the UIC Spelling rules, ISO2631 and evaluation standards of comfort for passenger dedicated line all over the world [2]. In fact, the comfort for passengers on board is not all about vibration and noise, and involves the many recessive factors such as riding space, lighting, and individuation service. Therefore, the multivariate and comprehensive evaluation should be done from the aspects of train performance, line quality, passenger service etc. Through the deep analysis and research of the above factors, the evaluation index systems of comfort for high-speed trains have been established and the relevant comprehensive evaluation model also has been proposed by the rough set theory and multidimensional coefficient theory in the paper.

## 2. Multivariate Comfort Evaluation of High-speed Train

### 2.1. Effect on Comfort for High-speed Train

Because of the particularity of operating environment, the comprehensive effects on comfort for high-speed train not only have car vibration, noise under the running state, but also include internal temperature, humidity, illumination, air pressure, air quality, including passenger demands for audio and video entertainment and personalized services [3]. By analyzing the interactive effect among high-speed train, passengers and environment, the physical comfort based on human kinetics has been set up, which stems from the vibration extent of passenger's active experience when the vibration is transferred to the body. The physiological comfort based on human physiology has also been provided, which comes from a series of medical symptom when the fluctuation of internal air pressure and noise act on passengers to make the mass of

passenger resonate for high-speed train. Meanwhile, the psychological comfort based on human psychology has been built according to a series of behaviors after the passenger's subjective judgment of the surroundings through vision, smell, and hearing. From the above, the evaluation index of multivariate comfort for high-speed train has been established, as is illustrated with Table 1.

**Table 1 Comprehensive Evaluation Index Systems of Comfort for High-speed Train**

Target Layer	Comprehensive Evaluation of Multivariate Comfort for High-speed Train				
	Physical Comfort	Physiological Comfort		Psychological Comfort	
Rule Layer	Operating Performance	Noise and Pressure	Air Quality	Interior Environment	Personalized Service
	Vibratility	Noise of Compartment	Temperature inside Car	Adaptability of Seat	Catering
	Stability	Noise of Cab	Humidity inside Car	Decoration inside Car	Information
Index Layer	Lateral Acceleration	Noise of Passage	Car Ventilation	Lighting	Ticketing
	Vertical Acceleration	Maximum Amplitude of Pressure	Air Cleanliness		Guiding
		Maximum Change Rate of Pressure			Entertainment VIP Service

The index system can separately reflect one of the specific characteristics for high-speed railway and make an objective and effective analysis of comfort for high-speed train with the corresponding evaluating methods.

**2.2. Limit of Multivariate Comfort Evaluation**

Development characteristics of high-speed train are decided by the positive and negative, incremental, coordinated and stable system capability according to the dynamics analysis for high-speed railway. In order to get the reasonable evaluation results on comfort, the grades are divided according to the maximum range which is gotten under the threshold of risk factors. The five-grade evaluation of comfort is selected in accordance with UIC513 [4].  $p_i$  is the level interval value that the intensity in each grade of the positive and negative criterion, incremental criterion, coordinated criterion and stable criterion is denoted respectively with "+" and "-", shown as Table 2.

Table 2. Grade Identification Interval Table of Comprehensive Evaluation of Comfort for High-speed Train

Grade	Positive and Negative	Increment	Coordination	Stability	Ranked Interval	Interval Value
First	Very Comfortable	+++++	+++++	+++++	+++++	( $p_4, \infty$ ) (0.8,1.0]
Second	More Comfortable	++++	++++	++++	++++	( $p_3, p_4$ ) (0.6,0.8]
Third	General	+++	+++	+++	+++	( $p_2, p_3$ ) (0.3,0.6]
Fourth	Less Comfortable	++	++	++	++	( $p_1, p_2$ ) (0.1,0.3]
Fifth	Uncomfortable	+	+	+	+	( 0, $p_1$ ) [0,0.1]

**3. Mathematical Principle of Multidimensional Coefficient**

**3.1. Multidimensional Coefficient**

$i_n$  with n indexes of the evaluation objects always satisfies the requirements of preference for independence. Thus, n indexes can be regarded as n dimensions  $\vec{i}_n$ , which can

be expressed by a utility function:  $\mu = c_1 \vec{i}_1 + c_2 \vec{i}_2 + \dots + c_n \vec{i}_n$ . In the above function,  $\mu$  is the utility function,  $\vec{i}_n$  is the dimension of the nth index  $i_n$ ,  $c_i$  is the review value of the corresponding indexes. Then the utility function  $u$  is called the multidimensional coefficient.

**3.2. Evaluation Model Based on Multidimensional Coefficient**

Suppose the scheme set of evaluating is  $A = (A_1, A_2 \dots A_m)$ , the evaluating index set is  $I = (I_1, I_2 \dots I_n)$  and its weighting vector is  $W = (W_1, W_2 \dots W_n)$ . (note:  $W_i \in (0, 1]$ ,  $\sum_{i=1}^n W_i = 1$ ). When the scheme  $A_i$  is evaluating by the index set, the review value is  $\mu = c_{i1} \vec{i}_1 + c_{i2} \vec{i}_2 + \dots + c_{in} \vec{i}_n$ . Thus, the decision matrix  $D$  is:

$$D = \begin{bmatrix} c_{11} \vec{i}_1 + c_{12} \vec{i}_2 + \dots + c_{1n} \vec{i}_n \\ c_{21} \vec{i}_1 + c_{22} \vec{i}_2 + \dots + c_{2n} \vec{i}_n \\ \vdots \\ c_{m1} \vec{i}_1 + c_{m2} \vec{i}_2 + \dots + c_{mn} \vec{i}_n \end{bmatrix}$$

Because of the meaning of each index is different and the calculation method of value is also different, the dimension of each index is ultimately different. Therefore, the correlation function must be constructed to make each index standardized to the extent of impartial measurement.

Suppose  $i_n$  is the effective index, then  $b_{ij} = c_{ij} / \sum_{k=1}^m c_{ik}$ . Suppose  $i_n$  is the cost index, then  $b_{ij} = \frac{1}{c_{ij}} / \sum_{k=1}^m \frac{1}{c_{ik}}$ . The decision matrix  $D = (c_{ij})_{m \times n}$  can be translated into the standardized matrix  $B = (b_{ij})_{m \times n}$ , which can consequently be transformed into the decision matrix of multidimensional coefficient  $\mu = b_{i1} \vec{i}_1 + b_{i2} \vec{i}_2 + \dots + b_{in} \vec{i}_n$ . Thus, the evaluation model based on multidimensional coefficient can be set up.

**3.3. Calculation Steps Based on Multidimensional Coefficient**

The specific calculation steps of the evaluation model are as follows.

Step 1: Determination of the weighting vector of index  $W = (W_1, W_2 \dots W_n)^T$ .

Step 2: Determination of the absolute ideal solution and the negative absolute ideal solution of each index. Define the positive ideal solution:  $\mu^+ = b_{11}^+ \vec{i}_1 + b_{12}^+ \vec{i}_2 + \dots + b_{1n}^+ \vec{i}_n$ , and  $b_r^+ = \max_{1 \leq k \leq m} (b_{kr})$ ,  $r = 1, 2, \dots, n$ . Define the negative ideal solution:

$$\mu^- = b_{11}^- \vec{i}_1 + b_{12}^- \vec{i}_2 + \dots + b_{1n}^- \vec{i}_n, \text{ and } b_r^- = \min_{1 \leq k \leq m} (b_{kr}), r = 1, 2, \dots, n.$$

Then, the absolute ideal solution is  $\mu^+ = 1\vec{i}_1 + 1\vec{i}_2 + \dots + 1\vec{i}_n$ , and the absolute negative ideal solution is  $\mu^- = 0\vec{i}_1 + 0\vec{i}_2 + \dots + 0\vec{i}_n$ .

Step 3: Distance calculation of the absolute ideal solution  $d_k^+$  and the negative absolute ideal solution from each decision scheme by using Hamming distance.

$$\text{Let } d(\mu_{kr}, \mu^+) = \sum_{r=1}^n (|b_{kr} - b_r^+|), \quad d_k^+ = W^T \cdot d(\mu_{kr}, \mu^+) = \sum_{r=1}^n (w_r |b_{kr} - b_r^+|);$$

$$\text{Let } d(\mu_{kr}, \mu^-) = \sum_{r=1}^n (|b_{kr} - b_r^-|), \quad d_k^- = W^T \cdot d(\mu_{kr}, \mu^-) = \sum_{r=1}^n (w_r |b_{kr} - b_r^-|) \dots$$

Step 4: According to the distance of the absolute ideal solution  $d_k^+$  and the negative absolute ideal solution from each decision scheme, the comprehensive evaluation index  $p_k$  ( $k = 1, 2, \dots, m$ ) can be calculated. Each decision scheme is sequenced and selected best by  $p_k$  [5]. The bigger  $p_k$  is, the better program is. The formula of  $p_k$  is  $p_k = d_k^- \cdot (d_k^+ + d_k^-)^{-1}$ .

#### 4. Evaluation Model of Comfort Based on Multidimensional Coefficient

The evaluation of comfort for high-speed railway is one of multi-index decision-making problems, of which the comprehensive evaluation and analysis can be done by the above models. When the data acquisition is processed according to the comprehensive evaluation index systems of comfort for high-speed train, the real-time data cannot be acquired completely and part of the indexes have default values and even most of the indexes have fuzzy characteristics due to the limit of objective conditions and acquisition methods. Thus, the data acquisition system in each layer of evaluation rule constitutes an incomplete information system, which has to be reduced accordingly to comprehensively evaluate the general comfort for convenience [6, 7].

##### 4.1. Evaluation Process

(1) Determination of reduction and weight of the evaluation indexes. On the basis of fundamental theories of rough set, such as knowledge, core, reduction, information and attributes, the evaluation index systems can be reduced by the optimized arithmetic with attributes and core and the weight of the corresponding indexes can be determined using the importance of attributes [8, 9].

(2) Establishment of multidimensional coefficient of comfort evaluation for high-speed train.  $N$  dominating evaluation indexes are abstracted from the evaluation index systems, which can be regarded as  $n$  dimensions. Thus, the mathematical model of comfort evaluation for high-speed train based on multidimensional coefficient can be constructed.  $\mu = c_1 \vec{i}_1 + c_2 \vec{i}_2 + \dots + c_n \vec{i}_n$

(3) Determination of review values. By the thought of Delphi and method of FAHP, 10 experts are invited as an expert group to make fuzzy judgment of multiple indexes with testing data of high-speed railway operation. Meanwhile, the review values determined by the experts will be gathered statistically without weight by the statistical method of experts' values. The coefficient of review values in each index will be achieved ultimately.

(4) In the light of calculation steps of multidimensional coefficient, the mathematical model of comfort evaluation for high-speed train is standardized. The absolute positive ideal solution and the negative absolute ideal solution of evaluation indexes are determined. The distance from each evaluation index to the absolutely positive ideal solution and to the negative absolute ideal solution can be calculated with Hamming distance.

(5) Calculation of comprehensive evaluation indexes. The result of comprehensive evaluation can be provided according to the limit of grade identification of comfort evaluation for high-speed train.

##### 4.2. Evaluation Examples

According to the mathematical model of comfort evaluation for high-speed train, the section from Beijingnan Railway Station to Tianjinnan Railway Station in Beijing-Shanghai high-speed railway has been chosen for comprehensive research. The line of the section spans 131.4km and the marshalling EMU CRH3-350 with 4 power cars and 4 drag cars has been adopted, of which the weight is 495 tons and the length is 200.6 meters. The maximum limit speed along the line is 350km/h and the limit speed in the tunnels is 300km/h.

(1) The comprehensive evaluation indexes of multivariate comfort for high-speed train built above can be reduced to achieve 13 comprehensive evaluation indexes by the optimized

arithmetic of kernel attributes, This as: Operating Vibratility; Operating Stability; Lateral Acceleration; Vertical Acceleration; Passenger Compartment Noise; Passage Noise; Maximum Amplitude of Pressure; Car Temperature; Car Humidity; Car Ventilation; Seat Adaptability; Car Lighting; Information Services.

Then, the multidimensional coefficient of comfort evaluation for high-speed train is set up, namely,  $\mu = c_1 \vec{i}_1 + c_2 \vec{i}_2 + \dots + c_{13} \vec{i}_{13}$ . Meanwhile, according to the weight of the evaluation indexes based on attribute importance, the weight of the above evaluation indexes can be respectively determined, that is to say,

$$W=(0.076,0.075,0.077,0.081,0.076,0.082,0.072,0.082,0.081,0.074,0.076,0.073,0.075)$$

(2) The testing data of CRH3-350 operation for Beijing-Shanghai high-speed railway has been referred to comprehensively evaluate the above 13 indexes. The corresponding review value is:

$$\mu = 0.74 \vec{i}_1 + 0.84 \vec{i}_2 + 0.92 \vec{i}_3 + 0.85 \vec{i}_4 + 0.87 \vec{i}_5 + 0.59 \vec{i}_6 + 0.21 \vec{i}_7 + 0.31 \vec{i}_8 + 0.87 \vec{i}_9 + 0.75 \vec{i}_{10} + 0.84 \vec{i}_{11} + 0.96 \vec{i}_{12} + 0.75 \vec{i}_{13}$$

Which can be standardized by using the correlation function to get:

$$\mu = 0.735 \vec{i}_1 + 0.797 \vec{i}_2 + 0.831 \vec{i}_3 + 0.825 \vec{i}_4 + 0.797 \vec{i}_5 + 0.613 \vec{i}_6 + 0.715 \vec{i}_7 + 0.726 \vec{i}_8 + 0.825 \vec{i}_9 + 0.713 \vec{i}_{10} + 0.815 \vec{i}_{11} + 0.875 \vec{i}_{12} + 0.731 \vec{i}_{13}$$

(3) The distance from each evaluation index to the absolutely positive ideal solution and to the negative absolute ideal solution is calculated by using Hamming distance,  $d_k^+ = 0.0105$ ,  $d_k^- = 0.0462$ .

(4) The comprehensive evaluation index can be calculated in accordance with the above formula, then  $P=0.8148, P \in (0.8, 1.0]$ . Therefore, the comprehensive evaluation result of comfort for high-speed train in the section from Beijingnan Railway Station to Tianjinnan Railway Station is between "very comfortable" and "more comfortable" and prefers to "more comfortable". From now, when the improvement of train facilities is focused on, the improvement of external conditions and personalized services is more important to make the indexes of interior air temperature, compartment humidity and pressure changes more scientific and standardized. The light sources in compartment will be ensured to be soft and harmonious. The systems of entertainment and customer service will be enhanced to improve the level of personalized services for passengers.

## 5. Conclusion

With the rapid development of high-speed railway in China, the research on train comfort with qualitative methods can't meet the actual needs currently. After the discussion of the fuzzy rough set and multidimensional coefficient theories, the evaluation model of comfort for high-speed train based on fuzzy reduction and multidimensional coefficient has been established under the consideration of the effects on comfort for high-speed train in this paper. The model not only makes the evaluation process more scientific, accurate, intuitive and convenient, but also provides theoretic reference on high-speed train design, line design, line choosing, optimization etc., which has important theoretic meaning and practical value for the development of high-speed railway.

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