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# Research on Consistency-Based Matchability Evaluation Method for Brake Valves of Heavy-Duty Trains

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## Abstract

To evaluate the matchability between brake valves and associated components of the brake system, a consistency-based matchability evaluation method for brake valves of heavy-duty trains was proposed in this paper. Considering the control accuracy and response speed of the brake system, characteristic parameters of the brake cylinder equilibrium pressure and the response time to reach 90% of the target brake cylinder pressure were extracted as evaluation indicators. The entropy weight method was adopted to allocate weights to evaluation indicators. The optimal Latin hypercube sampling method was used to design operating conditions, and the dual-factor impact of the equivalent output area and equivalent leakage diameter of brake valves on the evaluation indicators was analysed. The matchability of the brake valve was assessed, and the effectiveness of the evaluation method was validated. The proposed method holds significant guidance for the development and optimization of new brake valves.

**Keywords:** brake valve, matchability evaluation, evaluation indicator, weight distribution, optimal Latin hypercube sampling, heavy-duty trains.

## 1 Introduction

Higher capacity and faster speed are effective ways to enhance railway transport capacity. Actually, the operation of heavy-duty trains is not only influenced by traction and loading capacity but also limited by braking capability. The continuous development of heavy-duty transportation imposes higher demands on brake systems [1]. Currently, brake valves frequently encounter issues such as internal contamination with impurities, exhaust port blockage, spool valve seat peeling off, leakage caused by impurities abrasion, and poor sealing. The heavy-duty train failure rate analysis shows that the brake valve category has the largest proportion of brake system failures, up to 49.54% [2]. Hence, improving the performance and reliability of brake valves is vital for ensuring railway transport safety.

Innovating and optimizing the structural design of existing brake valves is an effective way to enhance performance and reliability. However, the matchability of newly optimized brake valves with other associated components in the brake system also influences train brake performance and operation safety. Therefore, developing a scientifically effective matchability evaluation method for train brake valves holds significant importance for enhancing the safety of heavy-duty train brake systems, and serves as a reference for the optimization design of brake valves.

As for matchability, most literature tends to use qualitative methods combined with simple numerical values, and rarely employ a quantitative scoring standard to clearly determine the performance levels of the evaluation objects. Moreover, scholars seldom focus on the matchability between brake valves and related components, and the only matching analysis of brake valves is also a simple comparison by test. Yang et al. [3] designed a set of system matching test equipment of the heavy-duty train brake system, and conducted performance tests under different working conditions. The matching and performance of the heavy-duty train brake system were evaluated by analysing the changing trend of the brake cylinder pressure curve. However, there are few pieces of literature that employ a numerical scoring method to evaluate the matchability between train brake valves and associated components of the brake system.

In this paper, a consistency-based matchability evaluation method for brake valves of heavy-duty trains was proposed by designing evaluation indicators and allocating weights. The remaining parts were organized as follows. Section 2 introduced the brake system of heavy-duty trains and the matchability evaluation method. Section 3 described case analysis to verify the proposed method. Finally, conclusions were drawn in Section 4, with some prospects on research and development.

# 2 Methods

## 2.1 Brake System of Heavy-duty Trains

The brake valve is the core component of the brake system, responsible for controlling air inflation, braking, releasing, and maintaining pressure. This paper focuses on the matching issue between the brake valve and the associated components in the brake system of heavy-duty trains. Associated components refers to the critical parts of the brake system other than the brake valve itself, primarily including the empty-load changeover valve module and the brake cylinder. The empty-load changeover valve module, which play a crucial role in ensuring the brake system responds to load changes and maintains the brake force balance, is composed of sensing valve, pressure limiting valve and bucking cylinder, etc.

The sensing valve converts the load information into an air pressure signal and sends it to the pressure limiting valve. The pressure limiting valve automatically adjusts the brake cylinder pressure based on the air pressure signal. The secondary air cylinder is responsible for storing and supplying the compressed air. The brake cylinder is the executing component of the brake system, converting the compressed air into brake force. In light-load or partially loaded conditions, the role of the bucking cylinder is to divert some of the compressed air from the brake cylinder, thereby reducing the brake cylinder pressure [4].

Under normal braking conditions, the core concept of the operational coordination between the brake valve and associated components is to balance the pressure of the brake cylinder with the sum of the air pressure of the bucking cylinder and the adjusting spring pressure of the sensing valve. In the empty-load condition, the pressure of the adjusting spring is lower, and the bucking cylinder needs to obtain more air pressure to balance the brake cylinder pressure. In the fully loaded condition, the sinking of the vehicle body increases the pressure value of the adjusting spring, the brake cylinder pressure is sufficient to balance without the need for pressure from the bucking cylinder. The mutual coordination between the brake valve and associated components achieves the automatic adjustment of brake pressure for different load conditions.

## 2.2 Consistency-based Matchability Evaluation Method

### 2.2.1 Design of Evaluation Indicators

To evaluate the matchability between the brake valve and associated components, it is essential to assess the effectiveness and quality of the braking function once they are matched. Therefore, the evaluation should focus on the brake cylinder. Considering the control accuracy and response speed, two key characteristic parameters of the brake cylinder equilibrium pressure $P$ and the response time to reach 90% of the target brake cylinder pressure $t$ were extracted as evaluation indicators.

The brake cylinder equilibrium pressure $P$ refers to the pressure when the brake cylinder gradually reaches a steady state, which can directly reflect the realization effect of the braking function. Moreover, $P$ will be different under different air source constant pressure, different pressure reduction and different load conditions, and these values have relevant standards and ranges. The response time to reach 90% of the target brake cylinder pressure $t$ refers to the time required for the valve to reach 90% of the target brake cylinder pressure from the start of braking, which reflects the response speed and rapid braking ability of the brake system.

### 2.2.2 Determination of Influence Factors

The influence factors in the matching evaluation primarily refer to those factors that cause changes in the evaluation indicators. During actual train operation, brake valves often encounter issues such as leakage due to wear from impurities or failures resulting from poor reliability of sealing components like rubber rings. These leakage problems can significantly affect the steady-state pressure value of the brake cylinder. Additionally, the brake valve may face contamination by impurities inside the valve body or blockage of exhaust ports during operation. These issues directly impact the exhaust area of the brake valve, thereby influencing the braking response time [5].

Given the status and issues faced by brake valves, the equivalent output area and the equivalent leakage diameter of the brake valve, which can directly reflect the working state of the brake valve, were determined as the influence factors.

### 2.2.3 Allocation of Indicator Weights

In this paper, the consistency analysis method is used to comprehensively evaluate the matching of brake valves, aiming at integrating various indexes into a unified measurement standard, aiming at integrating various indexes into a unified measurement standard. In the process of multi-index fusion, it is necessary to allocate the weight reasonably and scientifically. As two evaluation indexes focus on evaluating the size of braking force and braking response time respectively, it is difficult to judge the relative importance of these two indicators through experience, the method of objective weight allocation should be chosen to help improve the accuracy and credibility of the overall evaluation results.

The entropy weight method assigns weights based on the objectivity of data, which reduces the interference of human subjective factors. Moreover, it can systematically deal with each indicator to ensure that each indicator can accurately reflect its impact on the overall evaluation, avoiding some indicators being ignored or over-emphasized. Therefore, the entropy weight method was chosen to assign weights.

The allocation of weights using the entropy weight method includes the following steps:

(1) The standardization of indicator data.

A specific standardization method to convert raw data into a comparable standardized format was adopted. Through this process, data were transformed into dimensionless, magnitude-consistent, and positively additive standardized data. Additionally, indicator attributes may vary, such as positive indicators and negative indicators. A positive indicator means the greater the data value, the better, while a negative indicator is the opposite. To unify the analysis method, both evaluation indicators were converted into positive indicators and subsequently standardized accordingly.

(2) The weight allocation of evaluation indicators.

During the weight allocation phase, it is essential to accurately measure the impact of each indicator on the overall performance of the brake system. Theoretically, the more important an indicator is, the larger its weight should be. Before distributing the weights, evaluation indicators need to be normalized to ensure their values lie within the range of 0 to 1. After standardizing and normalizing, the entropy weight method requires a zero-sum shift operation on the data, ultimately yielding the processed data $u_{ij}$.Then, the numerical proportion $P_{ij}$ is calculated as follows.

$$P_{ij} = \frac{\mu_{ij}}{\sum_{i=1}^{a} \mu_{ij}},\ i = 1,2,\cdots,a; j = 1,2,\cdots,b \tag{1}$$

where $a$ represents the number of sample points, and $b$ represents the number of evaluation indicators.

After calculating the numerical proportion $P_{ij}$ , the entropy value of each evaluation indicator is calculated as follows.

$$e_j = -K \sum_{i=1}^{a} P_{ij} \cdot \ln P_{ij}, j = 1,2,\cdots,b \tag{2}$$

$$K = \frac{1}{\ln a} \tag{3}$$

where the proportional coefficient $K$ is related to the number of sample points $a$.

Next, the variation index $d_j$ is calculated using the Equation (4):

$$d_j = 1 - e_j, j = 1,2,\dots,b \tag{4}$$

Finally, the weight of each indicator $w_j$ is calculated using the Equation (5):

$$w_j = \frac{d_j}{\sum_{j=1}^{b} d_j}, j = 1,2,\dots,b \tag{5}$$

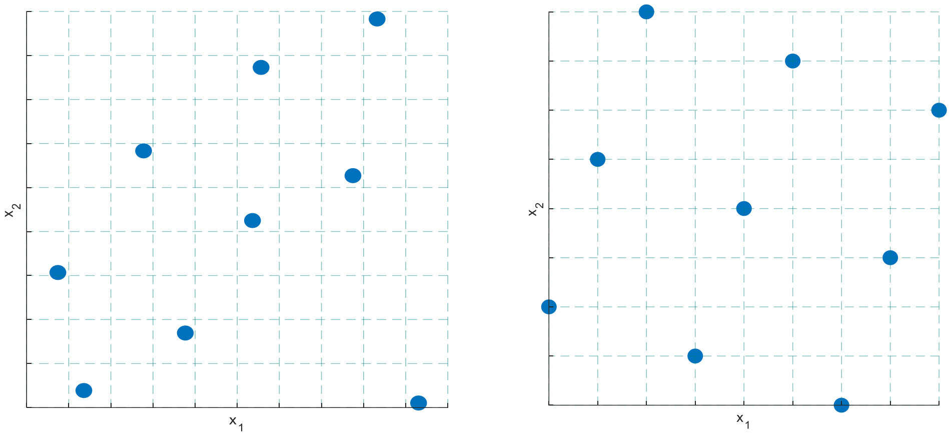
It can be observed that the entropy value of an indicator exhibits an inverse trend with the variation in its original data. If an indicator's original data has a wide range of variation, its corresponding entropy value tends to be smaller, and vice versa. Therefore, there is a complementary relationship between the weight of an indicator and its entropy value, which enhances the objectivity of the weight allocation.

### 2.2.4 Selection of Sample Points Under the Influence of Multiple Factors

The matchability between the brake valve and the associated components involve a comprehensive evaluation of multiple factors and indicators. When using the entropy weight method for the allocation of indicator weights, it is necessary to select sample points and extract the characteristic parameters of the evaluation indicators. To ensure the accuracy and effectiveness, the selection of sample points should fully consider the joint influence of multiple factors. Therefore, to accurately and efficiently determine the weight coefficients, choosing a reasonable and scientific sampling method is of utmost importance.

Currently, the widely used data sampling methods include simple random sampling (SRS), Latin hypercube sampling (LHS), and stratified sampling (SS). According to [6-8], SRS has low spatial coverage, which may lead to sample concentration. LHS significantly improves the dispersion of sample distribution and simplifies the calculation process compared to the SS while maintaining good probabilistic properties. Although SS performs best in terms of filling the sample space, its application in complex high-dimensional parameter spaces poses implementation challenges. Therefore, after comprehensive consideration, the LHS was adopted.

Moreover, although standard LHS is simple to implement, it performs relatively weakly in handling the uniformity of high-dimensional data, reducing pseudocorrelation, and extending samples. For this reason, many researchers have proposed various new algorithms to compensate for its shortcomings based on the fundamental framework of the LHS. Optimal Latin hypercube sampling (OLHS) methods focus on using optimization algorithms to refine the samples extracted by the LHS. The goal is to seek the optimal solution according to predefined functions, thereby obtaining a more uniformly and robustly distributed set of input samples. A comparison of the sampling effects between standard LHS and OLHS is shown in Figure 1.




(a) LHS (b) OLHS

Figure 1: Comparison of sampling effects before and after optimization.

In this paper, Euclidean distance is used as the measure of spatial dispersion. The aim is to maximize the minimal Euclidean distance between each new sample point and the existing sample points, thereby ensuring an optimal distance interval between the samples. Additionally, as shown in Equation (6), the empirical formula for the number of sample points from the Design of Experiments (DOE) module in Isight software was adopted.

$$c = d(d + 1)(d + 2) \tag{6}$$

where $c$ is the recommended number of sample points, and $d$ is the number of influencing factors.

The number of sample points obtained using Equation (6) not only ensures relative accuracy of the results but also enhances the experiment efficiency.

### 2.2.5 Formulation of the Comprehensive Evaluation Scoring Method

After determining the corresponding weights of the evaluation indicators, a consistency-based evaluation method that uses quantitative measures to assess the matching level of brake valves and associated components was constructed.

The core of the scoring standard is the linear weighting method, which is a practical and effective solution for multi-criteria decision-making problems. This method is particularly suitable for scenarios where diverse evaluation indicators need to be integrated into a comprehensive score. When evaluating the characteristics of brake valves, it can objectively reflect each valve's performance across various parameters and its overall performance level.

By setting the total score of the benchmark sample to a perfect 100 points as a comparison baseline, standardization and consistency were ensured in the evaluation process. Combining the indicator weights with linear weighting, the closer a valve's performance is to the benchmark value, the higher its score will be. This not only guarantees a fair evaluation of different valves but also accurately depicts the performance differences, thus broadly quantifying the characteristics of the brake valves.

The score of matchability evaluation is calculated as follows:

$$S = 100 \times W_{j1} \times \left(1 - \frac{|P_i - P_0|}{P_0}\right) + 100 \times W_{j2} \times \left(1 - \frac{|t_i - t_0|}{t_0}\right) \qquad (7)$$

where $S$ is the score, $W_{j1}$ is the weight of the brake cylinder equilibrium pressure, $W_{j2}$ is the weight of the response time to reach 90% of the target brake cylinder pressure. For the valve under evaluation, $P_i$ represents its brake cylinder equilibrium pressure, $t_i$ is the response time to reach 90% of the target brake cylinder pressure. Similarly, $P_0$ is the brake cylinder equilibrium pressure of the reference brake valve; $t_0$ is the response time of the reference brake valve.

# 3 Results

## 3.1 Construction of Matchability Analysis Model

Physical experiments are costly, time-consuming, and the test results are highly discrete, while the advantages of "high efficiency, low cost, and good flexibility" make model-based strategies gain more and more attention and application [9]. In order to accurately and comprehensively validate the proposed method, computer simulation method was adopted.

Among the computer modelling and simulation software related to brake systems, the context-oriented software AMESim provides a graphical modeling method based on the physical characteristics. It encompasses fundamental and specialized model libraries in fields like mechanical, hydraulic, and pneumatic systems. It supports the analysis of both steady-state and dynamic performance of complex systems or individual components [10]. Accordingly, AMESim software was used to construct the model for analysing the matchability of the brake valve and associated components.

Based on the combination of the brake valve and associated components and considering the principle of empty-load changeover valve and the parameter conditions required to meet demands of normal braking conditions, an equivalent braking valve and peripheral components simulation model for heavy-duty trains was established. The model mainly consists of a secondary air cylinder, bucking cylinder, sensing valve, pressure limiting valve, and brake cylinder, as shown in Figure 2.

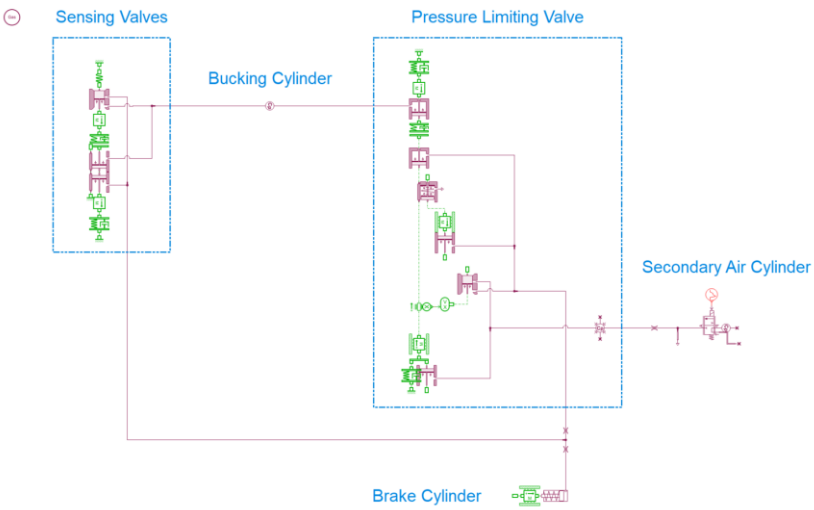


Figure 2: Simulation model for matchability analysis.

Based on the relevant conditions of common braking scenarios and the requirements of component parameters, the model was adjusted to achieve compatibility with constant air pressures of 500 kPa and 600 kPa. Under each constant pressure, it can accommodate different loads such as empty load, full load, and partially loaded states.

As shown in Figure 3, taking the empty load condition with a constant air pressure of 500 kPa as an example, the maximum pressure reduction is approximately 140 kPa, the bucking cylinder effectively diverts the air pressure, and the brake cylinder pressure ultimately stabilizes at around 170 kPa, which complies with the relevant standard specifications.

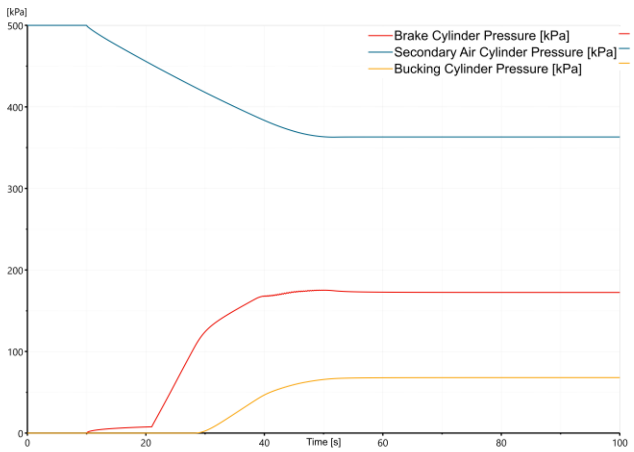


Figure 3: Pressure change curve for unloaded service brake with a set pressure of 500 kPa.

It can be seen that the brake valve in this parameter mode demonstrates good compatibility with different constant pressures. It can adjust to various load states, and the characteristic parameter values meet the requirements. Therefore, this equivalent brake valve, which meets the requirements of multiple scenarios, was set as the evaluation benchmark for subsequent brake valves. The specific values of its influence factors were as follows: the equivalent output area of the brake valve's outlet $X_1$ is 3 mm², and the equivalent leakage diameter $X_2$ is 0 mm. The equivalent output area $X_1$ and the equivalent leakage diameter $X_2$ of the equivalent brake valve were simultaneously changed and relevant experiments were conducted.

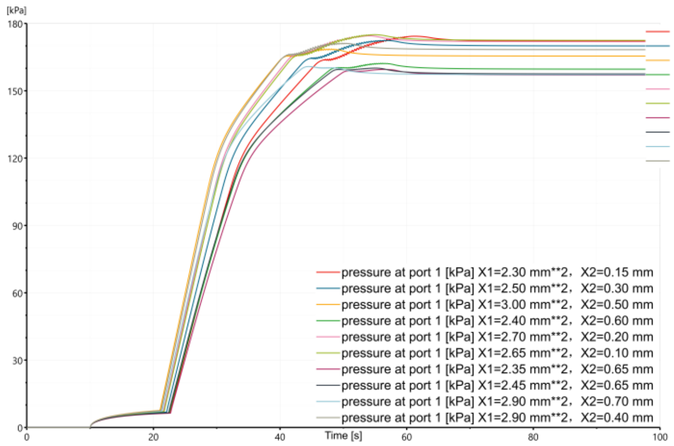



Figure 4: Dual factors influence of equivalent outlet area and equivalent leakage on brake cylinder air pressure change for brake valves.

As shown in the Figure 4, the sizes of the output area and the leakage diameter affect the evaluation indicators $P$ and $t$ , causing them to deviate from the benchmark values. This phenomenon not only demonstrates that the constructed model can be used for matchability analysis but also validates the significant effect of the determined influence factors on the evaluation results.

## 3.2 Selection of Sample Points

Before performing optimal Latin Hypercube Sampling, it is crucial to reasonably set the value ranges of the influencing factors, and it is usually based on the degree to which the influence factors affect the evaluation benchmark. Considering that if the equivalent output area $X_1$ is too small, it may significantly extend the braking response time; whereas if the equivalent leakage diameter $X_2$ is too large, the air pressure in the brake cylinder might drop to zero. Based on these considerations, the value ranges of each influencing factor were defined to ensure the rationality and effectiveness of the experimental design.

According to the Equation (6), as the value of the influencing factors $d$ is 2, the number of sample points $c$ is 24. Since the evaluation benchmark is needed, there should be a total of 25 sample points.

After determining the sampling range and the number of sample points, the sample points obtained using the OLHS method were shown in Figure 5.

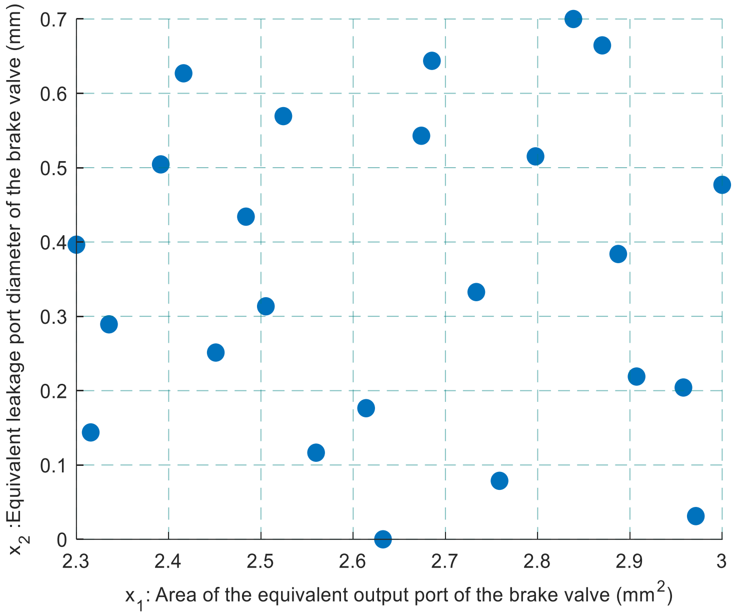


Figure 5: Selection of sampling points based on OLHS.

Based on the influence factor settings of the sample points and the benchmark point illustrated in Figure 5, simulation experiments were conducted and key characteristic parameters of the evaluation indicators were extracted. The specific results were detailed in Table 1.

| No. | $X_1$ (mm$^2$) | $X_2$ (mm) | $P$ (kPa) | $t$ (s) | No. | $X_1$ (mm$^2$) | $X_2$ (mm) | $P$ (kPa) | $t$ (s) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.000 | 0.0000 | 172.5102 | 26.2 | 14 | 2.674 | 0.5429 | 163.0596 | 31.3 |
| 2 | 2.300 | 0.3964 | 167.2646 | 34.7 | 15 | 2.685 | 0.6437 | 158.8365 | 32.9 |
| 3 | 2.315 | 0.1438 | 172.0993 | 33.3 | 16 | 2.733 | 0.3327 | 169.7870 | 29.0 |
| 4 | 2.335 | 0.2893 | 170.1537 | 33.5 | 17 | 2.759 | 0.0787 | 172.6895 | 28.2 |
| 5 | 2.391 | 0.5044 | 163.6795 | 34.6 | 18 | 2.798 | 0.5152 | 164.4759 | 29.6 |
| 6 | 2.416 | 0.6269 | 158.4358 | 36.6 | 19 | 2.839 | 0.7000 | 156.8822 | 32.3 |
| 7 | 2.451 | 0.2513 | 170.9018 | 31.8 | 20 | 2.870 | 0.6645 | 158.6373 | 31.1 |
| 8 | 2.484 | 0.4341 | 166.5020 | 32.5 | 21 | 2.887 | 0.3839 | 168.7332 | 27.8 |
| 9 | 2.505 | 0.3135 | 169.6837 | 31.4 | 22 | 2.907 | 0.2190 | 171.7477 | 27.1 |
| 10 | 2.524 | 0.5693 | 161.4771 | 33.7 | 23 | 2.958 | 0.2042 | 171.8455 | 26.6 |
| 11 | 2.560 | 0.1166 | 172.0785 | 30.3 | 24 | 2.971 | 0.0312 | 172.5858 | 26.4 |
| 12 | 2.614 | 0.1764 | 171.9049 | 29.7 | 25 | 3.000 | 0.4769 | 166.2208 | 27.4 |
| 13 | 2.632 | 0.0000 | 172.4533 | 29.5 | | | | | |

Table 1: Influencing factors and evaluation indicator of sampling points.

## 3.3 Allocation of Weight Coefficients

The entropy weight method was used to allocate weights to each evaluation indicator, and the weight coefficients of the indicators were shown in Table 2.

| Indicator | the brake cylinder equilibrium pressure $P$ | the response time to reach 90% of the target brake cylinder pressure $t$ |
|---|---|---|
| Weight | 0.54734 | 0.45266 |

Table 2: Weight distribution of evaluation indicators.

## 3.4 Comprehensive Evaluation Scoring

According to Equation (7), the final scores of 25 sampled points were calculated.

| No. | Influence factor $X_1$ (mm$^2$)、$X_2$ (mm) | Score | No. | Influence factor $X_1$ (mm$^2$)、$X_2$ (mm) | Score |
|---|---|---|---|---|---|
| 1 | $X_1$ =3.000， $X_2$ =0.0000 | 100 | 14 | $X_1$ =2.674， $X_2$ =0.5429 | 88.1902 |
| 2 | $X_1$ =2.300， $X_2$ =0.3964 | 83.6501 | 15 | $X_1$ =2.685， $X_2$ =0.6437 | 84.0859 |
| 3 | $X_1$ =2.315， $X_2$ =0.1438 | 87.6029 | 16 | $X_1$ =2.733， $X_2$ =0.3327 | 94.2984 |
| 4 | $X_1$ =2.335， $X_2$ =0.2893 | 86.6400 | 17 | $X_1$ =2.759， $X_2$ =0.0787 | 96.5194 |
| 5 | $X_1$ =2.391， $X_2$ =0.5044 | 82.6854 | 18 | $X_1$ =2.798， $X_2$ =0.5152 | 91.5767 |
| 6 | $X_1$ =2.416， $X_2$ =0.6269 | 77.5663 | 19 | $X_1$ =2.839， $X_2$ =0.7000 | 84.5025 |
| 7 | $X_1$ =2.451， $X_2$ =0.2513 | 89.8145 | 20 | $X_1$ =2.870， $X_2$ =0.6645 | 87.1326 |
| 8 | $X_1$ =2.484， $X_2$ =0.4341 | 87.2091 | 21 | $X_1$ =2.887， $X_2$ =0.3839 | 96.0373 |
| 9 | $X_1$ =2.505， $X_2$ =0.3135 | 90.1191 | 22 | $X_1$ =2.907， $X_2$ =0.2190 | 98.2031 |
| 10 | $X_1$ =2.524， $X_2$ =0.5693 | 83.5416 | 23 | $X_1$ =2.958， $X_2$ =0.2042 | 99.0980 |
| 11 | $X_1$ =2.560， $X_2$ =0.1166 | 92.7794 | 24 | $X_1$ =2.971， $X_2$ =0.0312 | 99.6305 |
| 12 | $X_1$ =2.614， $X_2$ =0.1764 | 93.7610 | 25 | $X_1$ =3.000， $X_2$ =0.4769 | 95.9312 |
| 13 | $X_1$ =2.632， $X_2$ =0.0000 | 94.2805 | | | |

Table 3: Score values of sampled sample valves.

As shown in Table 3, the comprehensive performance of each sample valve across different indicators could be seen clearly, which demonstrates the applicability and effectiveness of the proposed method.

# 4 Conclusions and Contributions

To evaluate the matchability between brake valves and associated components of the brake system, a consistency-based matchability evaluation method for brake valves of heavy-duty trains was proposed in this paper.

(1) Considering the control accuracy and response speed of the brake system, the brake cylinder equilibrium pressure and the response time were extracted as matchability evaluation indicators, and the entropy weight method was used to assign weights to each evaluation indicator.
(2) An equivalent simulation model for the heavy-duty train brake valve and its associated components was constructed, the OLHS method was used to design operating conditions, the dual-factor impact of the equivalent output area and equivalent leakage diameter of brake valves on the evaluation indicators was analysed, and the feasibility of the proposed evaluation method for multiple performance indicators was confirmed.
(3) The proposed method enabling a more intuitive comparison of the compatibility of each valve, thus providing a new perspective for analysing valve compatibility.

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