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Effectiveness evaluation of railway traffic safety based on the DEMATEL, AHP, and ANP methods

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Abstract: To improve railway traffic safety management of Taiwan, China, five key factors and eighteen secondary factors for traffic safety were identified based on the practical experiences of railway administrations in the European Union and Japan. The factor interdependence was calculated using the decision-making trial and evaluation laboratory (DEMATEL) and analytic hierarchy process (AHP) methods. Empirical studies were performed using the questionnaire. The analytical network process(ANP) method was used to evaluate the correlation degree and the relative weight ranking of each factor. The results show that safety risk management, top management commitment, safety responsibilities and key personnel, safety policy goals and resources, safety education and training, and aptitude management are the five most important factors to improve railway safety. Empirical results indicate that improving organizational culture is the leading determinant for increasing safety management effectiveness. Reviewing the current safety management systems, improving key personnel professionalism, and demonstrating the commitment of top management to safety are the key points. Continuous improvement and implementation of safety culture can gradually enhance the effectiveness of railway safety.

Key words: railway safety; safety management system (SMS); decision making trial and evaluation laboratory (DEMATEL) method; analytical hierarchy process (AHP) method; analytical network process(ANP) method

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The railway transportation industry of Taiwan, China, is vigorously promoting the safety management system(SMS), drawing on studies on long-term operation and verification of SMS in the United States, Japan, and the European Union(EU) as a significant guide to derive decision-making models to implement effective railway SMS for the railway operation industry in Taiwan, China[1]. The key factors to strengthen railway traffic safety effectiveness have been determined, and the railway SMS in this work has been compared with the effectiveness evaluation mechanism of SMS promoted by the aviation industry.

The European Union, the United Kingdom, the United States, and Japan attach great importance to management commitments and responsibilities, division of responsibilities, management supervision and organizational structure, identification of hazard factors, and risk assessment and mitigation measures, all the while paying attention to the eligibility management of employee education and safety training.

Regarding risk management, countries with advanced railway systems excel at identifying, assessing, and mitigating potential risk factors[2]; implementing comprehensive operational and evaluation specifications for systemic risk controls; implementing laws and regulations; managing equipment; and managing human factors such as safety and fatigue.

Effective safety consultation and communication, accident notification and investigation, and safety performance evaluation and monitoring require improving the efficacy of accident report investigation and notification, along with the collection, application, and dissemination of such reports. Such measures, along with encouraging worker participation in internal and external communications and safety performance evaluations and tracking, are essential to effectively improve railway traffic safety[3].

In 2018, the Institute of Transportation (IOT) in Taiwan, China, referred to countries with advanced railway development when proposing an overall framework for the railway of Taiwan, China SMS based on the plan-do-check-act cycle[4], including the following 12 key elements: safety policy objectives and resources; safety responsibilities and key personnel; safety risk management; safety education and training and capability management; communication and transfer of safety information; equipment management and operation management; safety documents; incident and accident reporting and investigation; change management; emergency response; review, audit, and evaluation; and continuous improvement[5].

Following the 2005 derailment in Amagasaki, Japan's Ministry of Land, Infrastructure, Transport and Tourism introduced an SMS to implement mechanisms for investigation after accidents and continuous safety improvement,

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establishing the foundation of a safety-oriented culture. As implemented by Japan Rail West, this system is designed to prioritize safety and thus prevent reoccurrences. By 2018, rail accidents were shown to have reduced by 2% to 3% annually[6]. In 2015, JRW further enhanced internal security audit operations and introduced third-party audits, eventually emphasizing five key areas for improvement through the subsequent eight years of implementation. The JRW experience in gradual active improvements to railway organization and safety has served as an important reference for railway authorities in Taiwan, China. This study focuses on the five main improvement areas proposed by the JRW audit, along with the SMS14 secondary items promoted by railway safety authorities in the EU and Japan and the SMS12 items promoted by the IOT Research of Taiwan, China, and eighteen secondary factors. The five leading areas for improvement are as follows: 1) Enhance safety management systems and improve the effectiveness of safety strategies, objectives and resources, safety responsibilities, and key personnel to ensure compliance with relevant laws and regulations. 2) Improve and enhance risk assessment, such as safety risk management, incident and accident reporting and investigation, and major accident response. 3) Improve the effectiveness of SMS audits, such as safety education, training and capacity management, equipment management, and management of operations, audits and reviews. 4) Improve internal and external communications processes, such as communication and dissemination of safety information, accident reporting, and continuous improvement of documentation and management. 5) Improve the organizational environment, enhance top management safety commitment, strengthen SMS maintenance training, encourage risk disclosure and solution development, establish positive awareness of safety management, and promote an organizational culture focused on safety.

1 Research Method Dimensions

Two questionnaires were designed using the decision-making trial and evaluation laboratory (DEMATEL) technique and analytical hierarchy process (AHP), establishing a framework from the results using matrix operations[7] to determine the degree of correlation and influence among various factors. Pairwise comparisons between pairs of elements were performed to establish comparisons through a comparison matrix to determine the associated eigenvectors and weights for use in a decision-making or evaluation index. Subsequently, ANP was utilized to calculate the supermatrix, construct the weight value, and calculate the degree of mutual influence, thereby constructing a decision-making analysis model that reflects real-world conditions. The questionnaires were distributed to scholars and industry experts with at least ten years of practical experience in railway transport systems and at least three years of experience in SMSs or who have performed verification and audit work related to SMSs. Of the 78 questionnaires distributed, 61 were returned, with an ultimate sample of 49 valid responses.

Chou et al.[8] analyzed a mental decision-making model of the elderly-friendly tourism industry planning by DEMATEL to explore the correlation between key factors and influence degree and calculated the weight and ranking of the secondary key factors by AHP. Ho[9] investigated the factors and preferences of ship registry selection by empirical analysis, collected the main considerations for the ship registry of Taiwan, China, employed DEMATEL for analysis of the correlation between the factors, and finally analyzed by AHP the impact of the key factors and preferences of registering ships in Taiwan, China. Tsai[10] used the MCDM method to explore the key decision-making factors of the financial institutions' views on international shipping investment, analyzed the mutual influence relationship between factors by DEMATEL, employed ANP to simplify the composition of each key factor in the questionnaire survey, and compared and obtained the supermatrix order and weight value of each factor.

In this work, the DEMATEL questionnaire was used to convert the influence degree of complex facets into the characteristics of causal relations and determine the core criteria between effective facets. Moreover, the DEMATEL method was adopted to explore the mutual influence between the five evaluation dimensions, obtain the influence coefficients between the dimensions, and establish a network structure.

The AHP questionnaire was employed to determine the relative importance of the decision-making characteristics in the hierarchy, establish a pairwise comparison matrix, calculate the eigenvalue and eigenvector, and conduct a consistency check, which can avoid decision-makers losing assessment accuracy by comparing multiple criteria at once. In the empirical research, the network structure of the evaluation dimension was established, and AHP was used to calculate the eigenvectors of the influencing factors as well as the weights of the factors included in the relevant dimension through the consistency test.

The weight of each factor was analyzed by ANP, and the priority order weight of all factors was obtained through super matrix operation for a comprehensive evaluation, and then the important factors that can improve the effectiveness were found.

2 Questionnaire and DEMATEL

Important defining factors and design measurement scales were chosen. Based on the literature and the questionnaires in this work, the different attributes of the possible effects were defined with the aim of establishing the attributes and measurement scales for the degree of influence. To further construct and calculate the matrix, each interviewed expert and scholar was asked to evaluate the direct effect between any two factors using integer scores, with 0 indicating "no influence," 1 indicating "weak influence," 2 indicating "medium influence," 3 indicating "strong influence," and 4 indicating "extremely strong influence" (see Tab. 1)[10].

Tab. 1 DEMATEL questionnaire

No.	Factor items	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
A	Security policy, goals, and resources		4	4	4	2	2	2	4	2	3	2	3	3	4	4	2	2	1
B	Safety responsibilities and key personnel	1		2	2	4	4	2	2	1	2	2	4	2	1	1	2	2	1
C	Ensure compliance with relevant laws and regulations	1	1		4	4	3	1	1	2	1	1	1	1	1	1	2	3	1
D	Security risk management	1	1	0		2	4	3	3	3	2	2	3	3	1	1	3	2	1
E	Incident and accident report and investigation	3	1	1	1		3	2	1	3	2	3	4	3	1	2	2	3	1
F	Response to major accidents and others	2	1	0	2	3		1	1	3	2	3	4	3	1	2	2	2	1
G	Safety education training and competency management	1	1	1	2	2	3		2	1	2	2	2	2	1	1	2	3	1
H	Equipment management and operation management	1	1	1	2	1	2	2		3	2	2	2	3	1	1	2	1	1
I	Audit, review, and evaluation	1	1	0	2	1	1	2	3		1	1	3	3	1	1	1	2	1
J	Communication and transmission of safety information	1	1	2	2	2	3	2	2	1		2	3	2	1	1	1	1	1
K	Accident and other information reporting	2	1	1	2	3	3	2	1	2	2		3	3	1	1	1	2	2
L	Continuous improvement	0	0	1	2	1	1	1	2	2	1	1		2	1	1	1	1	2
M	Document creation and management	0	0	1	2	1	1	2	2	1	3	3	2		1	3	1	1	1
N	Commitment from top management	4	2	1	3	1	3	3	2	2	3	3	1	2		3	2	1	1
O	Education and training required to maintain the safety management system	1	2	1	1	1	1	1	2	2	2	3	2	3	1		3	2	1
P	Encourage the discovery of risks and seek solutions	1	2	1	1	1	1	2	1	1	1	1	2	2	1	3		3	1
Q	Establish a positive awareness of safety management	1	2	1	1	2	3	3	1	3	3	3	3	2	2	2	1		2
R	Continuity and inheritance of organization culture	1	3	1	3	3	3	3	1	1	1	1	1	2	2	3	1	1	

Secondly, the direct-relation matrix $\boldsymbol{X}$ was established. The values defined in Tab. 1 were placed in the corresponding positions to generate the direct-relation matrix, wherein X_{ij} indicates the degree of influence of attribute i on attribute j. The diagonal attribute in the direct-relation matrix $\boldsymbol{X}$ was set to 0. Afterwards, the degree of influence between the different factors was obtained, and a direct relationship matrix was created.

$$\boldsymbol{X} = \begin{bmatrix} 0 & x_{12} & \dots & x_{1n} \\ x_{21} & 0 & \dots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{n1} & x_{n2} & \dots & 0 \end{bmatrix} \tag{1}$$

Thirdly, the normalized direct-relation matrix $\boldsymbol{N}$ was established. In the direct-relation matrix, the maximum value from the sum of the columns was derived. λ refers to the reciprocal of the maximum value. Multiplying the direct-relation matrix $\boldsymbol{X}$ by λ derives the final normalized direct-relation matrix $\boldsymbol{N}$.

$$\boldsymbol{N} = \lambda \boldsymbol{X} \tag{2}$$

Fourthly, the direct/indirect relation matrix $\boldsymbol{T}$ was established. After obtaining the normalized relation matrix $\boldsymbol{N}$, the direct/indirect relation matrix $\boldsymbol{T}$, which provides information about how one factor can affect another factor, and the total relation matrix were created using the unit matrix $\boldsymbol{I}$, which refers to a unit matrix (i.e., a matrix in which the diagonal value is 1 and others are zero). Mathematically, $\boldsymbol{T}$ can be calculated as

$$\boldsymbol{T} = \lim_{K \to \infty} (\boldsymbol{N} + \boldsymbol{N}^2 + \dots + \boldsymbol{N}^K) = \boldsymbol{N}(\boldsymbol{I} - \boldsymbol{N})^{-1} \tag{3}$$

Then, $\boldsymbol{D}_i$ and $\boldsymbol{R}_j$ and the influencing degree of the factors from the direct/indirect relation matrix $\boldsymbol{T}$ were calculated. After obtaining the direct/indirect matrix $\boldsymbol{T}$, as it was necessary to calculate the influence of one attribute on the other attributes and the degree of influence, $\boldsymbol{t}_{ij}$ is defined as attribute i, $j = 1, 2, \dots, n$ of the direct/indirect matrix $\boldsymbol{T}$. Furthermore, $\boldsymbol{D}_i$ refers to the sum of row i, which represents the sum of the other attributes affected by attribute i. $\boldsymbol{R}_j$ refers to the sum of row j, which represents the sum of attribute i affected by the other attributes. $\boldsymbol{D}_i$ and $\boldsymbol{R}_j$ were obtained from the direct/indirect matrix $\boldsymbol{T}$ and contained both direct and indirect effects.

$$D_i = \sum_{j=1}^{n} t_{ij} \qquad i = 1, 2, \dots, n \tag{4}$$

$$R_i = \sum_{i=1}^{n} t_{ij} \qquad j = 1, 2, \dots, n \tag{5}$$

Finally, the prominence $\boldsymbol{D} + \boldsymbol{R}$ and the relation $\boldsymbol{D} + \boldsymbol{R}$ were calculated. The prominence $\boldsymbol{D} + \boldsymbol{R}$ means the total degree of influence and the influence of the factor and shows the degree of the relationship between dimensions, the value of which can reveal the core degree and connection of the factor. Additionally, $\boldsymbol{D} + \boldsymbol{R}$ refers to the degree of cause, which shows the strength of the influence and the influence of the dimensions and represents the degree of difference between the influence and the influence of the factor (see Tab. 2).

Considering the arithmetic mean of the vertical axis $\boldsymbol{D} - \boldsymbol{R}$ and the horizontal axis $\boldsymbol{D} + \boldsymbol{R}$ intersecting the correlation degree $\boldsymbol{D} + \boldsymbol{R}$ as the new origin, the causal correlation diagram was divided into four quadrants.

Tab. 2 Prominence and relation values using the DEMATEL method

Key factors	Sum of column D	Sum of column R	Relevance of $D+R$	Influence of $D-R$	Ranking
A	7.078 0	5.314 0	12.392 0	1.764 0	2
B	6.922 2	5.901 3	12.823 5	1.021 0	3
C	5.634 2	5.740 1	11.374 3	0.105 9	7
D	6.514 8	6.408 8	12.923 6	0.106 1	5
E	6.247 1	6.430 8	12.677 9	0.183 7	9
F	6.478 4	6.597 6	13.076 0	0.119 2	8
G	6.227 4	6.167 7	12.395 1	0.059 7	6
H	5.390 4	6.476 1	11.866 5	1.085 7	18
I	5.816 5	6.215 5	12.032 0	0.399 0	10
J	5.438 9	6.328 4	11.767 3	0.889 5	16
K	5.700 8	6.620 3	12.321 1	0.919 5	17
L	5.983 9	6.691 5	12.675 4	0.707 6	14
M	5.305 6	6.030 4	11.336 0	0.724 8	15
N	6.876 8	4.905 6	11.782 5	1.971 2	1
O	6.424 8	6.211 8	12.636 6	0.212 9	4
P	5.386 1	5.951 5	11.337 6	0.565 4	13
Q	5.398 5	5.843 7	11.242 2	0.445 2	11
R	5.395 5	5.853 3	11.248 8	0.457 8	12

As shown in the causal correlation quadrant analysis in Fig. 1, it can be observed that the five dimensions that belong to the first quadrant have a relatively large degree of correlation in relative importance. A (security policy, goals, and resources), B (safety responsibilities and key personnel), O (education and training required to maintain the SMS), G (safety education training and competency management), and D (security risk management) are the five dimensions.

3 AHP Analysis

The first step in AHP analysis is to define the purpose, and a hierarchical model is developed to determine decisions. With this structure, comparisons can be made easily between the criteria and alternatives determined to achieve the goal. After developing the hierarchical structure, the questionnaire was designed. The content of each section of the subject was made to compare with each other, and the evaluation scale was divided into nine levels. Tab. 3 shows the comparison matrix for the determining criteria. In a matrix with n elements, $n(n-1)/2$ comparisons were made.

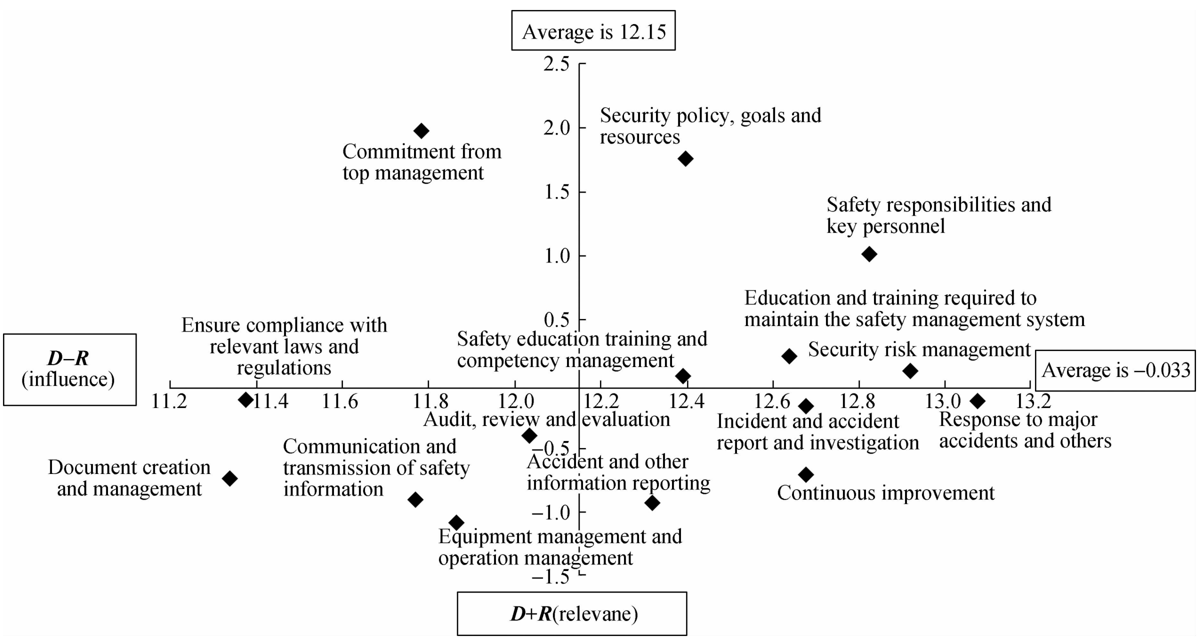

Fig. 1 Analysis of the causal quadrant of the influence degree and correlation degree of key factors

Tab. 3 AHP evaluation scale description

Evaluation scale	Definition	Importance comparison explanation
1	Equal importance	Contributions of the two comparative factors are equally important: Equally
3	Weak importance	Experience and judgment are slightly inclined to think of a certain factor: Moderately
5	Essential importance	Experience and judgment are slightly inclined toward a certain factor: Strongly
7	Great importance	Actually shows an intense tendency toward a certain factor: Demonstratively
9	Demonstrated importance	Enough evidence to be absolutely certain about a certain factor: Extremely
2, 4, 6, 8	Intermediate value	When a compromise value is required

Based on AHP, the eigenvalues and eigenvectors of the comparison matrix help determine the priority order. The eigenvector corresponding to the largest eigenvalue determines the priorities[11].

The purpose of this is to systematize complex problems and to hierarchize each evaluation aspect of each problem. Hierarchy is applied to divide different levels for pairwise comparison. Based on the previous analysis of the research topic and the questionnaire's design, 5 main criteria and 18 secondary criteria were established to form a complete and operational hierarchical structure.

The results of the relative importance of each factor were obtained from the questionnaire, and then a pairwise comparison matrix was established. The values used in the pairwise comparison are 1/9, 1/8, …, 1/3, 1/2, 1, 2, …, 8, 9, and the measurement of the comparison results of n elements was placed in the upper triangular part of the comparison matrix $\boldsymbol{A}$ [12]; that is, $a_{ji} = 1/a_{ij}$, where $\boldsymbol{W}$ is the eigenvector of $\boldsymbol{A}$. Moreover, the elements of the matrix for pairwise comparisons are as follows:

$$\boldsymbol{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} \frac{W_1}{W_1} & \frac{W_1}{W_2} & \cdots & \frac{W_1}{W_n} \\ \frac{W_2}{W_1} & \frac{W_2}{W_2} & \cdots & \frac{W_2}{W_n} \\ \vdots & \vdots & & \vdots \\ \frac{W_n}{W_{1d}} & \frac{W_n}{W_2} & \cdots & \frac{W_n}{W_n} \end{bmatrix} \tag{6}$$

where

$$a_{ij} = \frac{W_i}{W_j},\ a_{ij} = \frac{1}{a_{ji}},\ \widetilde{\boldsymbol{W}} = \{W_1, W_2, \ldots, W_n\}^{\mathrm{T}}$$
$$i, j = 1, 2, \ldots, n \tag{7}$$

After the pairwise comparison matrix was obtained, the priority vector of each level element was calculated. If λ is the eigenvalue of pairwise comparison matrix $\boldsymbol{A}$, then

$$(\boldsymbol{A} - \lambda \boldsymbol{I})\boldsymbol{W} = \boldsymbol{0} \tag{8}$$

The approximate method for calculating the maximum eigenvalue $\lambda_{\max}$ is to multiply the pairwise matrix $\boldsymbol{A}$ and the priority vector $\boldsymbol{W}$ to obtain a vector $\boldsymbol{W}'$ and then divide each element of $\boldsymbol{W}'$ by each element of the original priority vector $\boldsymbol{W}$. Finally, the maximum eigenvalue $\lambda_{\max}$ was calculated by averaging the obtained values.

$$\boldsymbol{AW} = \boldsymbol{W}' \tag{9}$$

$$\lambda'_{\max} = \frac{1}{n}\left(\frac{w'_1}{w_1} + \frac{w'_2}{w_2} + \ldots + \frac{w'_n}{w_n}\right) \tag{10}$$

Based on the AHP-calculated weight ranking of each key factor in Tab. 4, the top 10 items in descending order are as follows: E represents incident and accident report and investigation. P represents encourage the discovery of risks and seek solutions. J represents communication and transmission of safety information. K represents accident and other information reporting. M represents document creation and management. A represents security policy, goals, and resources. D represents security risk management. O represents education and training required to maintain the SMS. B represents safety responsibilities and key personnel. N represents commitment from top management.

Moreover, in this work, a consistency examination was performed. The consistency index (C) is a number that tells us how far we are from the consistent matrix. Mathematically, the consistency index is a function from a set of judgmental matrices to a set of real numbers. There is a direct effect on C if we change an element of the matrix. If any upper triangular entry of the matrix increases, then C must always be increasing, always decreasing, or decreasing to a minimum and then increasing. Therefore, there should be a unique local minimum in C functions. If the consistency measure exceeds the threshold value, then the earlier judgments must be changed. The idea of a consistency measure is meaningless without the thresholds associated with it. C can be

Tab. 4 AHP evaluation element weight ranking sequence

Evaluation groups	Evaluation elements	Weights	Sequence
C1	E1-1 Security policy, goals, and resources	0.113	5
	E1-2 Safety responsibilities and key personnel	0.128	2
	E1-3 Ensure compliance with relevant laws and regulations	0.077	15
C2	E2-1 Security risk management	0.119	4
	E2-2 Incident and accident report and investigation	0.950	10
	E2-3 Response to major accidents and others	0.085	11
C3	E3-1 Safety education training and competency management	0.079	14
	E3-2 Equipment management and operation management	0.083	12
	E3-3 Audit, review, and evaluation	0.084	13
C4	E4-1 Communication and transmission of safety information	0.102	8
	E4-2 Accident and other information reporting	0.105	7
	E4-3 Continuous improvement	0.069	18
	E4-4 Document creation and management	0.111	6
C5	E5-1 Commitment from top management	0.141	1
	E5-2 Education and training required to maintain the safety management system	0.122	3
	E5-3 Encourage the discovery of risks and seek solutions	0.098	9
	E5-4 Establish a positive awareness of safety management	0.071	17
	E5-5 Continuity and inheritance of organization culture	0.072	16

calculated using the equation below, where $\lambda_{\max}$ refers to the largest eigenvalue and n refers to the order of the matrix.

$$C = \frac{\lambda'_{\max} - n}{n - 1} \qquad (11)$$

Thus, the content of the returned expert questionnaires in this study is consistent and stable. For C and R of the 18 key factor dimensions, both are no more than 0.1. Then, the average of the other eigenvalues must be zero; hence, $C = 0$. The random consistency index (R') is the average of these C of the matrices of the same order.

$$R = \frac{C}{R'} \qquad (12)$$

4 Calculation of the Limit Supermatrix by ANP

Firstly, the network structure of the subject of this research was established. ANP is a decision-making mechanism that considers the correlation between relevant factors and the feedback relationship in decision-making at the same time[12].

Then, pairwise comparison matrices were established. The relative weights of each matrix were normalized and detected, which are given by the right eigenvector ($\boldsymbol{W}$) associated with the largest eigenvalue:

$$\boldsymbol{A}\boldsymbol{W} = \lambda_{\max}\boldsymbol{W} \qquad (13)$$

The equality of the ANP output largely depends on the consistency of the pairwise comparison of judgments. The consistency has to do with the relationship between the entries of $\boldsymbol{A}$: $a_{ij}a_{jk} = a_{ik}$. The consistency index is obtained through the following formula:

$$C = \frac{\lambda_{\max} - n}{n - 1} \qquad (14)$$

Tab. 5 lists the calculation results. If the evaluation factors exhibit no correlation in the questionnaire, the pairwise comparison of the submatrices value is 0. Tab. 6 shows the operation.

Tab. 5 AHP consistency verification

Key dimensions	C	R'	R	Consistency exam
A	0.004	1.120	0.037	Feasible
B	0.056	0.580	0.096	Feasible
C	0.005	0.580	0.008	Feasible
D	0.004	1.120	0.037	Feasible
E	0.057	0.520	0.091	Feasible
F	0.027	0.046	0.580	Feasible
G	0.004	1.130	0.042	Feasible
H	0.056	0.580	0.096	Feasible
I	0.005	0.550	0.012	Feasible
J	0.079	0.900	0.081	Feasible
K	0.027	0.042	0.680	Feasible
L	0.005	0.680	0.015	Feasible
M	0.003	1.150	0.032	Feasible
N	0.056	0.570	0.086	Feasible
O	0.027	0.056	0.680	Feasible
P	0.025	0.580	0.008	Feasible
Q	0.017	0.580	0.011	Feasible
R	0.003	1.150	0.032	Feasible

Tab. 6 Unweighted supermatrix

Level		C1			C2			C3			C4				C5				
		E1-1	E1-2	E1-3	E2-1	E-2	E2-3	E3-1	E3-2	E3-3	E4-1	E4-2	E4-3	E4-4	E5-1	E5-2	E5-3	E5-4	E5-5
C1	E1-1	0.211	0.239	0.241	0.235	0.314	0.316	0.359	0.327	0.326	0.305	0.293	0.267	0.254	0.262	0.262	0.211	0.239	0.241
	E1-2	0.106	0.161	0.098	0.582	0.618	0.106	0.161	0.098	0.296	0.417	0.377	0.420	0.582	0.618	0.106	0.161	0.098	0.296
	E1-3	0.404	0.400	0.355	0.418	0.382	0.404	0.400	0.355	0.331	0.279	0.330	0.313	0.418	0.382	0.404	0.400	0.355	0.331
C2	E2-1	0.427	0.582	0.582	0.211	0.239	0.241	0.582	0.618	0.373	0.211	0.582	0.618	0.106	0.161	0.098	0.296	0.618	0.373
	E2-2	0.573	0.418	0.418	0.106	0.161	0.098	0.211	0.239	0.241	0.106	0.418	0.382	0.404	0.400	0.355	0.331	0.296	0.241
	E2-3	0.582	0.618	0.106	0.404	0.400	0.355	0.106	0.161	0.098	0.404	0.211	0.239	0.241	0.582	0.618	0.373	0.331	0.098
C3	E3-1	0.418	0.382	0.404	0.427	0.582	0.618	0.404	0.400	0.355	0.427	0.106	0.161	0.098	0.211	0.239	0.241	0.373	0.355
	E3-2	0.211	0.239	0.241	0.582	0.618	0.373	0.161	0.098	0.098	0.573	0.404	0.400	0.355	0.106	0.161	0.098	0.241	0.355
	E3-3	0.106	0.161	0.098	0.211	0.239	0.241	0.400	0.355	0.355	0.211	0.427	0.582	0.618	0.404	0.400	0.355	0.098	0.296
C4	E4-1	0.404	0.400	0.355	0.106	0.161	0.098	0.618	0.582	0.618	0.106	0.161	0.427	0.582	0.618	0.404	0.400	0.355	0.331
	E4-2	0.427	0.582	0.618	0.404	0.400	0.355	0.382	0.418	0.382	0.404	0.400	0.355	0.211	0.239	0.241	0.582	0.618	0.373
	E4-3	0.114	0.127	0.114	0.000	0.427	0.582	0.618	0.161	0.098	0.427	0.582	0.618	0.106	0.161	0.098	0.211	0.239	0.241
	E4-4	0.277	0.211	0.239	0.241	0.573	0.418	0.382	0.400	0.355	0.573	0.418	0.382	0.404	0.400	0.355	0.106	0.161	0.098
C5	E5-1	0.211	0.239	0.211	0.239	0.241	0.239	0.241	0.211	0.239	0.241	0.239	0.241	0.427	0.582	0.618	0.404	0.400	0.355
	E5-2	0.106	0.161	0.106	0.161	0.098	0.161	0.098	0.106	0.161	0.098	0.161	0.098	0.106	0.161	0.098	0.106	0.161	0.098
	E5-3	0.404	0.400	0.404	0.400	0.355	0.400	0.355	0.404	0.400	0.355	0.400	0.355	0.404	0.400	0.355	0.404	0.400	0.355
	E5-4	0.427	0.582	0.427	0.582	0.618	0.582	0.618	0.427	0.582	0.618	0.582	0.618	0.427	0.582	0.618	0.427	0.582	0.618
	E5-5	0.573	0.418	0.573	0.418	0.382	0.418	0.382	0.573	0.418	0.382	0.418	0.382	0.573	0.418	0.382	0.573	0.418	0.382

The weighted supermatrix was normalized by the column of the initial supermatrix. The weighted supermatrix can be calculated using

$$\boldsymbol{W}^{w} = (\boldsymbol{W}_{y}^{w})_{n \times n} \qquad (15)$$

Tab. 7 lists the calculation results.

Tab. 7 Weighted supermatrix

Level		C1			C2			C3			C4				C5				
		E1-1	E1-2	E1-3	E2-1	E-2	E2-3	E3-1	E3-2	E3-3	E4-1	E4-2	E4-3	E4-4	E5-1	E5-2	E5-3	E5-4	E5-5
C1	E1-1	0.104	0.115	0.093	0.235	0.314	0.316	0.070	0.064	0.064	0.148	0.142	0.130	0.123	0.147	0.146	0.104	0.115	0.093
	E1-2	0.116	0.129	0.146	0.415	0.295	0.376	0.069	0.089	0.069	0.202	0.183	0.203	0.185	0.245	0.260	0.116	0.129	0.146
	E1-3	0.104	0.115	0.093	0.104	0.146	0.104	0.115	0.093	0.146	0.104	0.115	0.093	0.093	0.167	0.104	0.115	0.093	0.056
C2	E2-1	0.116	0.129	0.146	0.116	0.056	0.116	0.129	0.146	0.056	0.116	0.129	0.146	0.146	0.391	0.116	0.129	0.146	0.063
	E2-2	0.391	0.308	0.056	0.391	0.115	0.093	0.308	0.056	0.115	0.093	0.308	0.056	0.056	0.043	0.146	0.104	0.115	0.093
	E2-3	0.104	0.115	0.093	0.000	0.129	0.146	0.104	0.115	0.129	0.146	0.104	0.115	0.104	0.115	0.056	0.116	0.129	0.146
C3	E3-1	0.116	0.129	0.146	0.000	0.308	0.056	0.116	0.129	0.308	0.056	0.116	0.129	0.116	0.129	0.115	0.093	0.308	0.056
	E3-2	0.104	0.115	0.093	0.308	0.391	0.308	0.056	0.116	0.115	0.093	0.308	0.056	0.391	0.308	0.129	0.146	0.104	0.115
	E3-3	0.116	0.129	0.146	0.104	0.115	0.093	0.391	0.391	0.129	0.146	0.104	0.146	0.104	0.115	0.093	0.056	0.116	0.129
C4	E4-1	0.391	0.308	0.056	0.116	0.129	0.146	0.063	0.045	0.308	0.056	0.116	0.056	0.116	0.129	0.146	0.104	0.115	0.093
	E4-2	0.277	0.254	0.277	0.391	0.146	0.104	0.115	0.093	0.350	0.391	0.308	0.115	0.093	0.308	0.056	0.116	0.129	0.146
	E4-3	0.114	0.127	0.114	0.350	0.056	0.116	0.129	0.146	0.063	0.350	0.391	0.129	0.146	0.104	0.115	0.093	0.308	0.056
	E4-4	0.277	0.296	0.351	0.000	0.115	0.093	0.308	0.056	0.391	0.308	0.056	0.308	0.056	0.116	0.129	0.146	0.104	0.115
C5	E5-1	0.104	0.115	0.093	0.000	0.129	0.146	0.104	0.115	0.140	0.254	0.275	0.291	0.291	0.000	0.146	0.104	0.115	0.093
	E5-2	0.116	0.129	0.146	0.000	0.308	0.056	0.116	0.129	0.087	0.262	0.241	0.224	0.224	0.000	0.056	0.116	0.129	0.146
	E5-3	0.104	0.115	0.093	0.056	0.043	0.391	0.308	0.056	0.350	0.391	0.308	0.056	0.350	0.391	0.115	0.093	0.308	0.056
	E5-4	0.116	0.129	0.146	0.391	0.308	0.056	0.043	0.063	0.056	0.350	0.391	0.308	0.056	0.043	0.129	0.146	0.104	0.115
	E5-5	0.391	0.308	0.056	0.391	0.308	0.056	0.350	0.391	0.308	0.056	0.043	0.063	0.308	0.056	0.308	0.056	0.116	0.129

The weighted supermatrix was raised to power until the value of each row converged and leveled off, and the limit supermatrix was obtained. Using the connotation values of different column vectors in the limit supermatrix, all the weight values of facets and factors can be obtained.

When the previous unweighted supermatrix contains information about the covered plan, the odd ratios of all plans can be obtained. The supermatrix was calculated accordingly. The eigenvector values for the elements in the j-th group were compared with those for the elements in the i-th group. As the influence degrees among criteria in the total-influence matrix $\boldsymbol{W}_i$ are different [13], all criteria of the total-influence matrix $\boldsymbol{W}_i$ should be normalized. The normalized elements of the total-influence matrix $\boldsymbol{W}_i$ are as follows:

$$w_j^i = \frac{w_{ij}^p}{\sum_{i \to 1}^{n} W_{jJ}^P} \tag{16}$$

Tab. 8 lists the calculation results.

Tab. 8 Limit supermatrix

Level		C1			C2			C3			C4				C5				
		E1-1	E1-2	E1-3	E2-1	E-2	E2-3	E3-1	E3-2	E3-3	E4-1	E4-2	E4-3	E4-4	E5-1	E5-2	E5-3	E5-4	E5-5
C1	E1-1	0.093	0.079	0.128	0.093	0.141	0.128	0.128	0.079	0.128	0.093	0.141	0.128	0.079	0.079	0.128	0.093	0.141	0.128
	E1-2	0.141	0.079	0.128	0.093	0.141	0.128	0.141	0.128	0.141	0.079	0.128	0.093	0.141	0.128	0.141	0.141	0.141	0.141
	E1-3	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.093	0.104	0.126	0.079	0.104	0.104	0.104	0.104	0.104	0.104	0.104
C2	E2-1	0.117	0.104	0.128	0.000	0.117	0.117	0.093	0.141	0.093	0.093	0.141	0.000	0.141	0.141	0.128	0.104	0.141	0.128
	E2-2	0.121	0.128	0.118	0.128	0.121	0.121	0.141	0.141	0.079	0.128	0.093	0.141	0.128	0.093	0.093	0.104	0.126	0.118
	E2-3	0.105	0.118	0.074	0.118	0.105	0.105	0.104	0.141	0.141	0.141	0.093	0.104	0.126	0.141	0.141	0.083	0.114	0.126
C3	E3-1	0.128	0.074	0.128	0.074	0.128	0.104	0.093	0.104	0.128	0.141	0.141	0.093	0.093	0.141	0.104	0.141	0.093	0.093
	E3-2	0.118	0.128	0.118	0.117	0.118	0.093	0.104	0.093	0.079	0.128	0.093	0.141	0.128	0.079	0.128	0.093	0.141	0.128
	E3-3	0.074	0.000	0.074	0.000	0.074	0.141	0.093	0.141	0074	0.079	0.128	0.093	0.141	0.128	0.141	0.141	0.141	0.141
C4	E4-1	0.093	0.128	0.093	0.128	0.117	0.128	0.141	0.128	0.117	0.128	0.128	0.128	0.128	0.074	0.128	0.093	0.128	0.093
	E4-2	0.141	0.118	0.079	0.128	0.093	0.141	0.128	0.118	0.118	0.093	0.181	0.079	0.128	0.093	0.141	0.128	0.118	0.141
	E4-3	0.079	0.128	0.093	0.141	0.128	0.141	0.128	0.074	0.074	0.141	0.128	0.074	0.093	0.093	0.093	0.079	0.093	0.079
	E4-4	0.141	0.117	0.093	0.118	0.141	0.079	0.118	0.117	0.128	0.079	0.118	0.117	0.141	0.141	0.141	0.141	0.141	0.141
C5	E5-1	0.126	0.121	0.141	0.074	0.121	0.141	0.128	0.074	0.118	0.141	0.105	0.104	0.079	0.079	0.079	0.126	0.000	0.126
	E5-2	0.093	0.000	0.079	0.117	0.104	0.126	0.118	0.093	0.074	0.126	0.117	0.093	0.141	0.141	0.141	0.093	0.093	0.093
	E5-3	0.141	0.141	0.141	0.141	0.118	0.093	0.074	0.141	0.117	0.093	0.141	0.141	0.126	0.126	0.126	0.093	0.104	0.126
	E5-4	0.128	0.128	0.126	0.128	0.074	0.074	0.117	0.128	0.128	0.128	0.128	0.128	0.093	0.093	0.093	0.141	0.093	0.093
	E5-5	0.118	0.118	0.093	0.11	0.128	0.117	0.068	0.118	0.118	0.118	0.118	0.118	0.118	0.086	0.141	0.093	0.093	0.105

DEMATEL, AHP, and ANP were applied to analyze the questionnaire results and identify correlation values and weights among the 18 key factors, with an overall comparative analysis summarized in Tab. 9.

Tab. 9 Overall priority dimension ranking

Main key indicators	Weights	Ranking	Key factors	Each dimension		Overall	
				Weights	Ranking	Weights	Ranking
Strengthen the safety management system and improve its effectiveness	0.199 4	2	Security policy, goals, and resources	0.089 8	4	0.022	4
			Safety responsibilities and key personnel	0.097 7	3	0.018	3
			Ensure compliance with relevant laws and regulations	0.011 8	15	0.045	13
Improvement and enhancement of hazard assessment	0.140 3	3	Security risk management	0.107 8	2	0.014	1
			Incident and accident report and investigation	0.021 7	11	0.029	7
			Response to major accidents and others	0.011 1	16	0.057	18
Improvement of the effectiveness of safety management system audit	0.106 4	5	Safety education training and competency management	0.048 4	7	0.025	5
			Equipment management and operation management	0.009 7	17	0.047	15
			Audit, review, and evaluation	0.048 7	6	0.037	10
Improvement of the organization's internal and external communication process	0.115 7	4	Communication and safety information	0.017 6	13	0.052	17
			Accident and other information reporting	0.015 6	14	0.049	16
			Continuous improvement	0.079 6	5	0.032	8
			Document creation and management	0.004 7	18	0.039	11
Improve the organization's ambiance	0.436 5	1	Commitment from top management	0.392 8	1	0.017	2
			Education and training required to maintain the safety management system	0.043 6	8	0.026	6
			Encourage the discovery of risks and seek solutions	0.041 3	9	0.046	14
			Establish a positive awareness of safety management	0.021 5	12	0.041	12
			Continuity and inheritance of organization culture	0.040 7	10	0.035	9

5 Conclusions

1) From the empirical research, the primary factors based on the main key indicators to implement SMS are an improvement of organizational ambiance (organizational culture shaping) followed by strengthening of the entire management system and improvement of its effectiveness, improvement of risk assessment, improvement of the internal and external communication process, and improvement of the effectiveness of SMS audit.

2) Moreover, by empirical analysis of the fifteen key factors discussed, the top five most important overall evaluations are the following: security risk management; commitment from top management; safety responsibilities and key personnel; security policy, goals, and resources; and safety education training and competency management.

3) As for management responses to the assessment of key factors, observing the right of each dimension, the proportion of top management commitment and safety responsibility and key personnel far exceeds the other factors. It can be observed that in the implementation of an SMS, human factors can provide resources and committed leadership and key personnel with expertise is a top priority.

4) Safety risk management is also weighted highly, indicating that railway operating organizations still need to strengthen checks on safety risk management operations. This means that before the implementation of SMS operations, railway operating organizations still need to strengthen pragmatic risk management operations.

5) Among the main key factors, the improvement of rent culture is bigger than the other four items in the final weighted evaluation. Moreover, 43% of the questionnaires showed that the key to improvement is to improve the organizational atmosphere, which, together with safety culture, undoubtedly becomes the basis for long-term development and the most important factor for improving the effectiveness of the SMS.

6) The railway-related industries of Taiwan, China have attached great importance to improving railway safety. Through this research on the key important factors of the SMS index weight and evaluation mechanism, the existing railway units cooperate to adjust the SMS key implementation operations and gradually implement the safety culture construction and atmosphere improvement of the overall operation organization. It is found that the overall railway traffic operational safety and effectiveness are gradually improving.

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基于 DEMATEL、AHP 和 ANP 方法的铁路行车安全有效性评估

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摘要：为加强中国台湾地区铁路交通安全管理体系的有效性，基于欧盟和日本的实践经验，整理出 5 个主要关键因素和 18 个次要关键因素. 采用多标准决策实验方法和层次分析法，计算各因素的相互依赖性，并结合问卷进行实证分析. 使用分析网络过程方法评估各因素之间的相关性，并进行相对权重排序. 结果表明，提高铁路安全的 5 个最重要因素依次为安全风险管理、最高管理层的承诺、安全责任与关键人员、安全政策目标与资源、安全教育训练与适任性管理. 调查问卷显示，提升有效性的关键在于改善组织文化. 检验现有铁路安全管理系统作业、提升关键人员的专业水平与展现最高管理层决心是首要推动重点，持续推进落实安全文化才能逐步提升铁路安全的有效性.

关键词：铁路安全；安全管理系统；决策实验室法；分析层级程序法；分析网路过程方法

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