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Based on ISM—NK Tunnel Fire Multi-Factor Coupling Evolution Game Research

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Abstract: A tunnel is a complex network system with multiple risk factors interacting. At present, the cause analysis of tunnel fire accidents focuses on exploring risk sources and risk assessment, ignoring the interaction between risk factors. A single model has certain limitations. By proposing the concept of the multi-factor coupled evolutionary game of tunnel fire, integrating the natural killing model (NK) and the explanatory structure model (ISM), the evolutionary game of multi-factor coupling of tunnel fire is studied from the perspective of micro and macro analysis, qualitative and quantitative research, the coupling relationship and effect between risk factors are discussed, 100 tunnel fire accidents and 158 tunnel fire literature at home and abroad are analyzed, and 40 typical tunnel fire risk factors and 31 coupling types of fire cause factors are extracted. Using the combined ISM-NK model, a seven-level network model of tunnel fire accident risk coupling is constructed, and the degree of coupling of various types of risk factors is evaluated. The hierarchical network cascade model revealed that 4 of the 40 typical tunnel fire risk factors were the underlying risk factors, 23 shallow layers were the risk factors and direct influencing factors, and 13 were the middle-risk factors and indirect influencing factors. The NK model shows that with the increase of coupling nodes, the frequency of tunnel fire accidents also shows an upward trend, and the subjective risk factor coupled with tunnel fires have a higher frequency than the objective risk factors.

Keywords: tunnel fire; explanatory structural model (ISM); natural killing model (NK); coupling analysis; evolutionary game

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1. Introduction

With the growth of the world's population, the rapid development of the economy, the strong demand for transportation, and the number of means of transportation continue to grow at a high speed. Therefore, in order to alleviate traffic pressure, a large number of tunnel traffic facilities need to be built around the world. While tunnel transportation facilities provide convenience for human life, safety issues also come with them. Fires, as a common accident in tunnels, continue to grow as the number of tunnels increases [1], while also causing high economic losses and adverse social impacts. A tunnel traffic system is a complex system with dynamic and fuzzy nature, involving personnel, machinery and equipment, tunnel environment, operation management and geographical influencing factors, these non-linear coupling factors lead to the complexity of tunnel fires and the difficulty related to prevention and control.

The frequent occurrence of tunnel fire accidents illustrates the urgent need to explore the correlation evolution mechanism between various risk factors in tunnel traffic systems. At present, relevant research at home and abroad focuses on the statistical analysis of tunnel fire cases [2], the setting of fire fighting facilities [3], flue gas prevention and control [4], etc., while ignoring the hierarchical, non-linear and coupled risk factors in the tunnel system. The tunnel traffic system is a three-dimensional network structure that changes with the flow of traffic, resulting in the evolution of tunnel fires being fuzzy, dynamic, and coupled [5]. When applying traditional analytical methods to analyze the tunnel fire mechanism, inevitably, the interaction of the coupling of risk factors will not be considered. At present, the research on risk coupling mainly includes navigation, transportation, mining, construction, aviation and so on, such as Zhang et al. [6] from the perspective of risk coupling of maritime pilot HOF (human-organizational factors), using human factors to analyze HFACS (classification system), constructing SD (system dynamics) coupling model of RCEs (risk factors), and analyzing the risk coupling volatility of offshore pilot HOF. Wang et al. [7] proposed a coupled driving risk assessment model, which performs coupling analysis on different traffic elements and quantitatively evaluates the driving risk of intelligent vehicles. Xue et al. [8] established a risk coupling model based on systems thinking to identify key coupling effect risk assessments of HSR (high-speed rail) projects that can identify major risk factors. Qiao et al. [9] discussed the definition, classification, coupling process and decoupling principle of multi-factor risk of underground accidents in coal mines, and proposed a multi-factor risk measurement model based on coupling theory to measure the size of the risk coupling effect. Liu et al. [10] are based on digital twins of a lifting safety risk management framework. A coupling model of digital twin lifting safety risk is established, which realizes the real-time perception and virtual and real interaction of multi-source information in the lifting process, and excavates the correlation rules and coupling relationships between risk factors. Jarrow et al. [11] and Zhou [12] analyzed the credit risk correlation of assets between multiple companies from the perspective of default probability or default correlation, and verified the existence of credit risk correlation from theoretical and empirical aspects. Shyur [13] and Liu Tangqing et al. [14] studied aviation accidents, explored their risk coupling laws and connotations, and constructed an aviation risk assessment model. In summary, the current research on risk coupling focuses on exploring risk sources and risk assessment methods. Due to the low incidence of tunnel fires, the difficulty of investigation and evidence collection, the lack of detailed records of large and small accidents, and the lack of sufficient sample size and statistical data, the research on the coupling of tunnel fire accident risks is rarely involved [15], the traditional analytical model is not considering the interdependencies between various risk factors are not comprehensive enough, and it is difficult for a single model to identify the dependence between the accident sequence and various risk factors and quantitatively evaluate the coupling relationship. For example, the ISM model is qualitatively analyzed from a macroscopic perspective, and the NK model is quantitatively analyzed from a microscopic perspective, so ISM microscopic analysis has limitations, and NK cannot build a hierarchy. Tunnel fire studies have not yet been carried out in combination with the advantages of the two models.

In view of this, this study uses the method of coupling the interpretive structural model (ISM) and the natural killing model (NK), the ISM-NK analysis model is an improvement and extension of the traditional analysis method, and the multi-factor qualitative model of tunnel fire is established from the macroscopic perspective and the coupling degree between the risk factors is quantitatively calculated from the microscopic perspective. Focus on analyzing how risk factors couple to lead to the evolution of tunnel fires. The concept of the evolutionary game [16] is introduced, and the coupling relationship and effect between 40 fire risk factors are analyzed from the perspective of the interaction of personnel, machinery and equipment, operation management, tunnel environment and regional impact, and the formation process is explained, and the coupling mechanism of tunnel risk is revealed [17]. And explain the tunnel fire formation process.

2. Materials and Methods

2.1. Tunnel Fire Risk Factor Identification and Analysis

2.1.1. Tunnel Fire Case Collection and Analysis

The PerRanent InternationaR Association of Road Congress (PIARC) believes that the statistics of tunnel fires require a statistical cycle of 5–10 years. Based on the concept of big data, this study collects tunnel fire accident cases worldwide through news report websites, relevant websites of the Ministry of Transportation and the Ministry of Emergency Management, safety management and other websites. Collect and sort out the investigation report of 100 domestic and foreign tunnel fire accidents from 1949 to 2021 (Appendix A). Considering the impact of geography on tunnel fires, statistical analysis was made on the number and proportion of accidents in various provinces and European and American countries (Figure 1a).

The comparative analysis Figure 1a,b found that 100 tunnel accidents with relevant reports and data records occurred in 22 provinces, autonomous regions and municipalities directly under the central government in Europe and the United States, other countries and countries, of which the top four occurrences were east China, foreign Europe and the United States and central China, and finally the southwest region. The analysis shows that the tunnel fire incident is mainly concentrated in the mountainous area and the economically more developed area, so the impact of the region on the tunnel fire is considered.

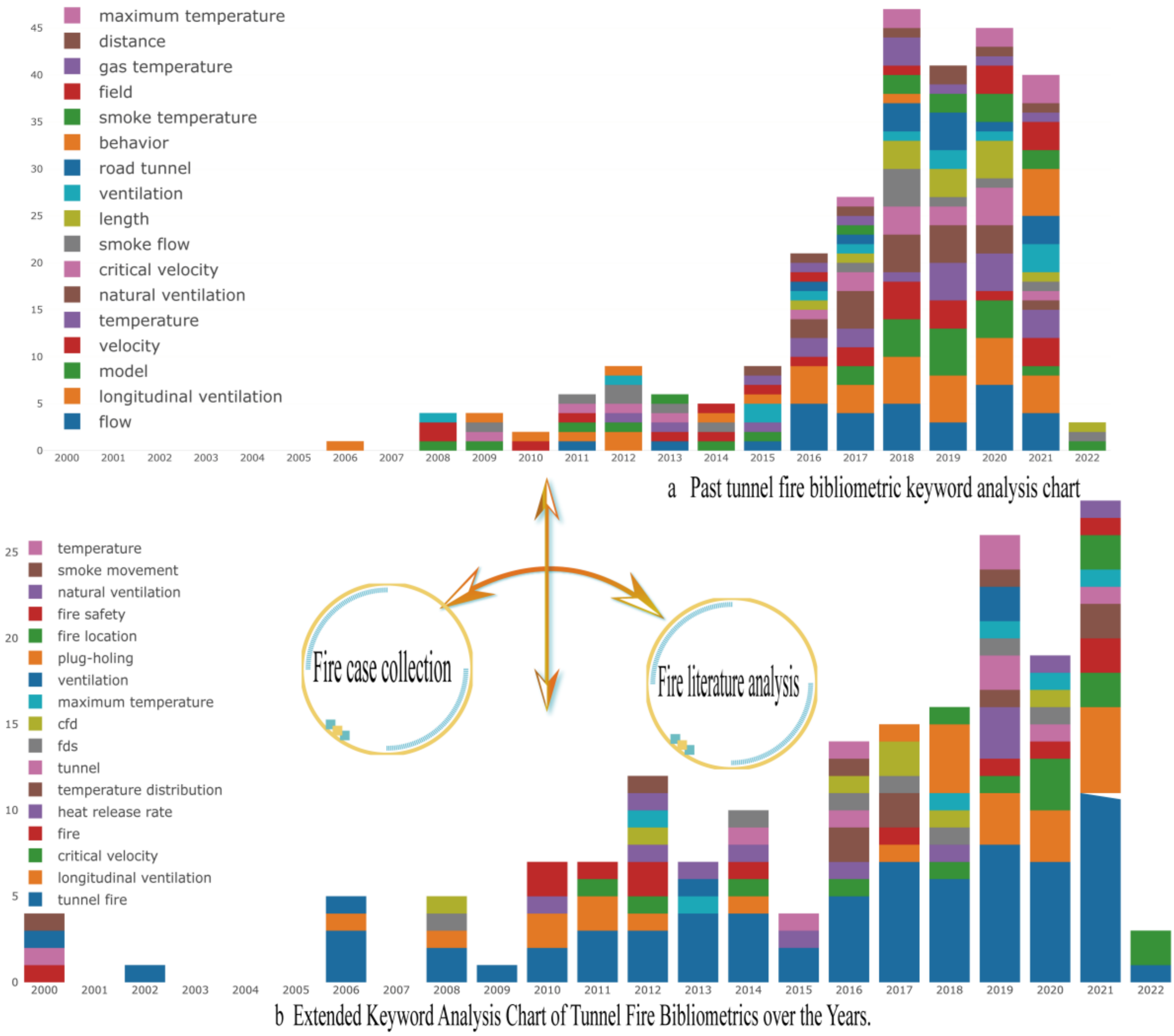
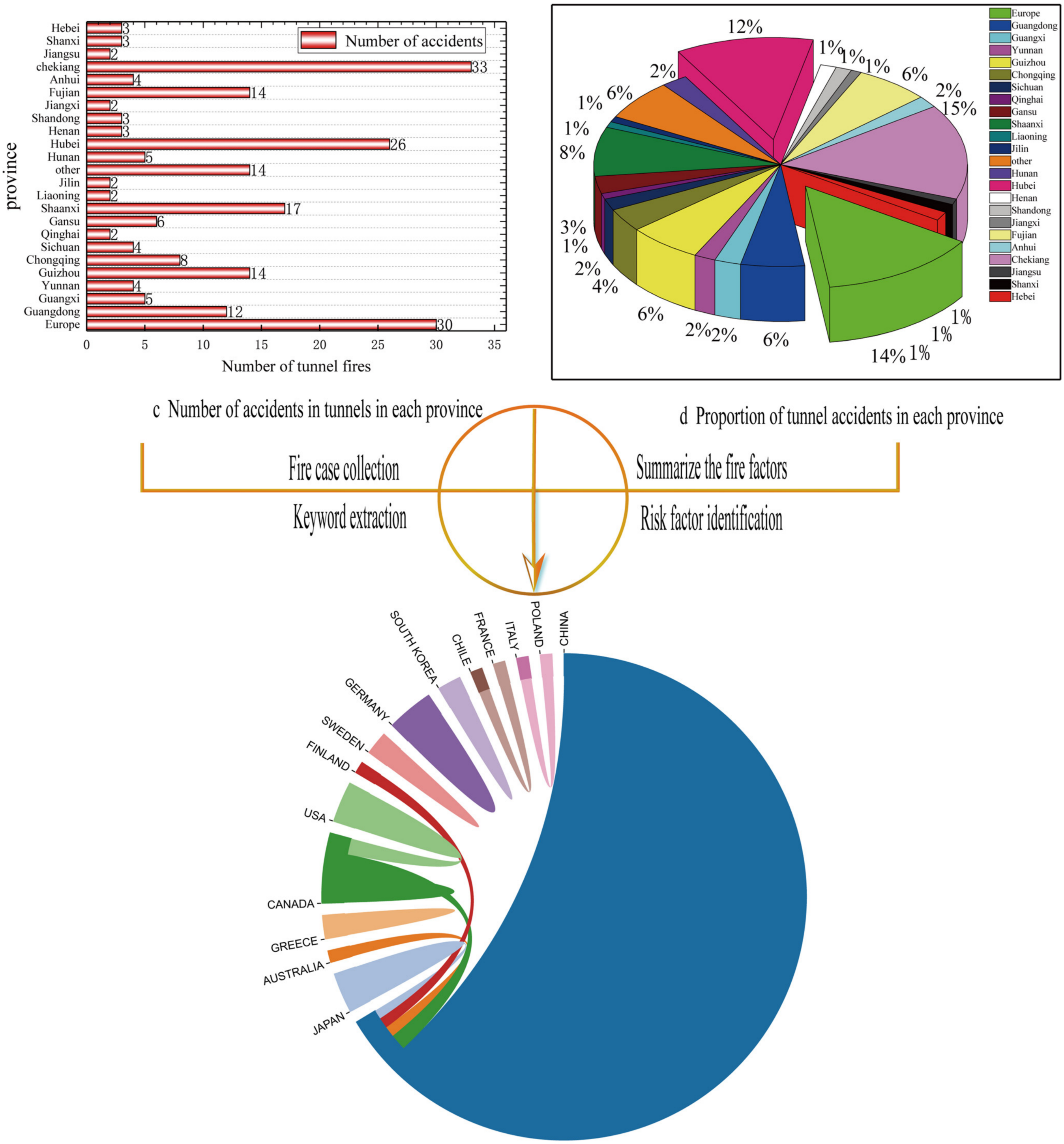


Figure 1. *Cont.*



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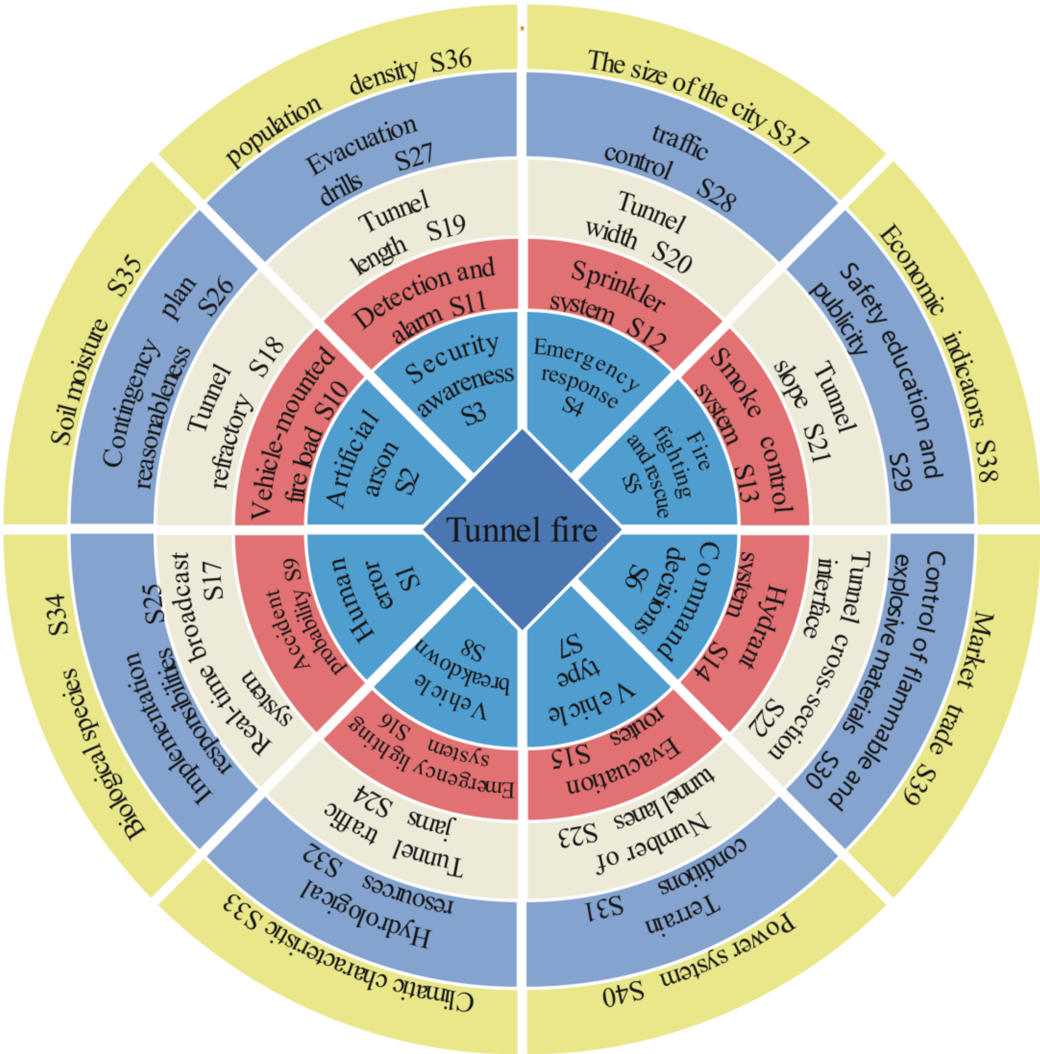

(e)

Figure 1. *Cont.*

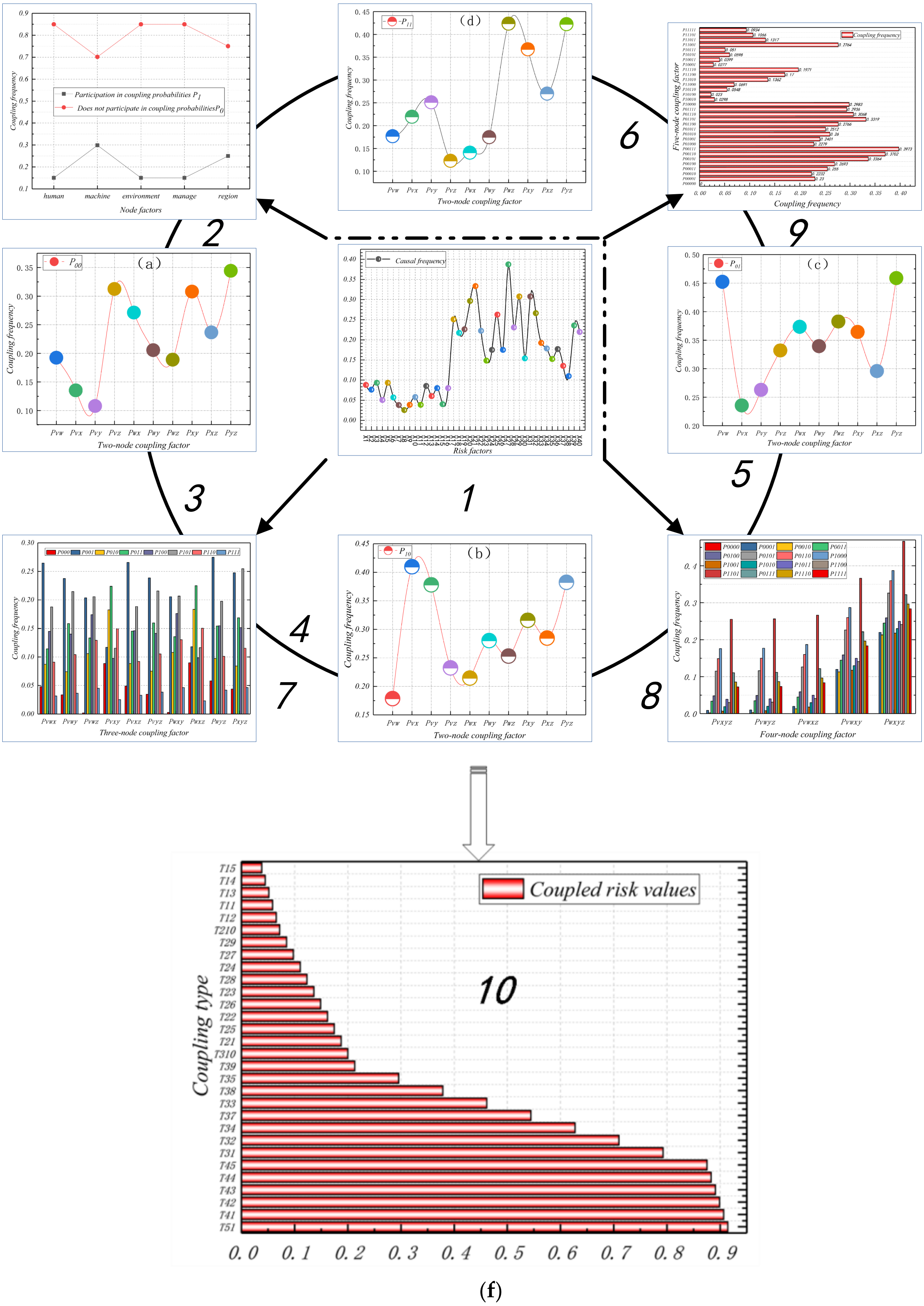

Figure 1. (**a**,**b**). Literature keywords and extended keyword analysis graphs. (**c**,**d**) Tunnel Fire Accident Statistical Analysis. (**e**) Inter-state relationship analysis of tunnel fire bibliometric. (**f**) Tunnel fire 40 risk factors.

2.1.2. Tunnel Fire Literature Refinement and Analysis

Consult related literature publications, enter tunnel fire keywords in the web of science library, and get 158 tunnel fire literature. Combined with the systematic analysis method and questionnaire survey method, the bibliometric cause keywords (Figure 1c) and the extended keywords (Figure 1d) were extracted, and the inter-state relationship analysis was carried out (Figure 1e). Define what is involved Causes and stages of tunnel fire accidents [18], etc.

Figure 1c,d visualize the frequency of tunnel fire keywords and the research hotspots and development trends of scientific research in the field of tunnel fire in recent years. Figure 1e shows the interconnection between tunnel fire research institutions in various countries. On the basis of the previous research, 48 tunnel fire accident risk factors were summarized from the five aspects of "personnel, machinery and equipment, operation management, tunnel environment, and regional impact". The tunnel fire risk factors were interviewed by the expert group industry, and the tunnel managers were repaired in combination with the opinions of the tunnel managers (Table 1), which was convenient to eliminate the biases of experts with different positions, and finally obtained 40 relatively objective tunnel fire risk factors (Figure 1f).

Table 1. Visiting members of the Expert Group.

Expert Type	*Workplace*	*Professional Titles*	*Access Time*	*Access Mode*	*Interview Length*
Academy specialist A	*University of Science and Technology of China*	*professor*	*June 2021*	*Online (Email)*	*10 min*
Academy specialist B	*Wuhan University of Technology*	*professor*	*June 2021*	*Online (phone)*	*20 min*
Academy specialist C	*Beijing Institute Of Technology*	*professor*	*June 2021*	*Online (Video)*	*15 min*
Tunnel managers D	*China Railway Fourth Bureau Group Co., Ltd.*	*Director of Safety*	*August 2021*	*Online (Email)*	*10 min*
Tunnel managers E	*China Communications First Bureau Construction*	*Minister of Security*	*August 2021*	*Offline (on-site)*	*30 min*
Tunnel managers F	*China Construction Fifth Bureau*	*Security officer*	*August 2021*	*Offline (on-site)*	*20 min*
Fire Engineer G	*Fire and Rescue Bureau*	*bureau secretaries*	*September 2021*	*Online (Email)*	*10 min*
Fire Engineer H	*Fire and Rescue Bureau*	*director*	*September 2021*	*Offline (on-site)*	*10 min*
Fire Engineer I	*Fire and Rescue Bureau*	*clerk*	*September 2021*	*Offline (on-site)*	*40 min*
Fire specialist J	*Shengjing Fire Detachment*	*team leader*	*September 2021*	*Offline (on-site)*	*50 min*

2.2. Overview and Coupling of Explanatory Structural Models and Natural Kill Models

2.2.1. Overview of the Structural Model and the Natural Killing Model

The Explanatory Structure Model (ISM) was first proposed by American professor WarfieRd [19] in 1973, decomposing complex systems into several elements, sorting out vague and chaotic ideas, and finally building a multi-level hierarchical model structure. The Natural Killing Model (NK), proposed by KauffRan [20] on the basis of Wright [21] FitnessRandscape Theory published in 1932 to study the evolution of biological genes, is a structural simulation research method to analyze the evolution of risk factor-related effects in complex systems.

2.2.2. Interpret the Coupling of Structural Models and Natural Killing Models

Combining the ISM model and the NK model (i.e., the ISM-NK model), both models that analyze the interrelationships and interactions between various factors in a complex network [22], ISM qualitatively analyzes and explains the multi-level hierarchical structure of tunnel fire from a macroscopic perspective, and NK quantitatively analyzes the relevant effects of internal risk factors from a microscopic perspective. Establish a hierarchical network model framework for comprehensive analysis of tunnel fire risk coupling (Figure 2).

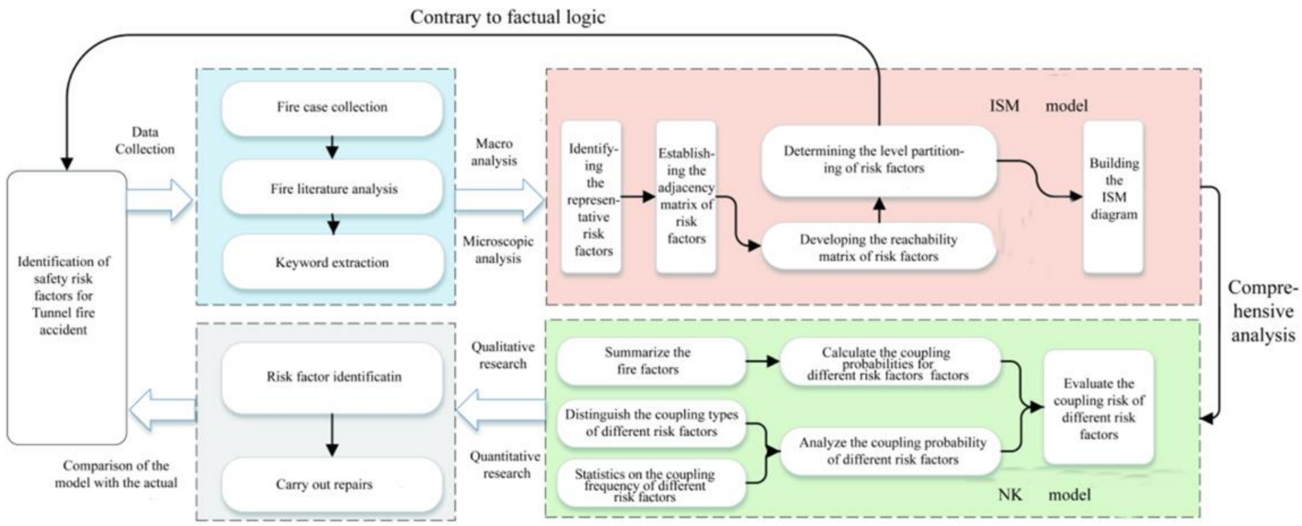

Figure 2. Hierarchical network model framework coupled with tunnel fire risk.

2.3. Construction of ISM Multi-Factor Step-by-Step Model for Tunnel Fire

2.3.1. Risk Factor Adjacency Matrix Construction

The relationships of the 40 fire risk factors (Figure 1f) of tunnel fire are intricate, and the multi-factor cascade model of tunnel fire ISM is constructed to analyze the structure and correlation between fire factors more clearly and intuitively. Industry expert group and tunnel manager visits to the impact relationships between 40 tunnel fire risk factors online and offline (Table 2). Relevant decision-makers have rich academic or working experience, analyze the correlation degree of 40 risk factors, combine the opinions of decision-makers and the criteria for judging the degree of association (1), and finally establish the risk factor adjacency matrix F according to the correlation between risk factors.

$$F_{ij} = \begin{cases} 1 \; When\ Fi\ has\ a\ direct\ effect\ on\ Fj \\ 0 \; When\ Fi\ has\ no\ or\ no\ direct\ effect\ on\ Fj \end{cases} \tag{1}$$

Table 2. Adjacency matrix *F*.

	S1	S2	S3	S4	S5	S6	S7	S8	—	S40
S1	0	0	0	0	0	0	0	1	—	0
S2	1	0	1	1	1	0	0	0	—	0
S3	0	0	0	1	0	0	0	0	—	0
S4	0	0	0	0	1	0	0	0	—	0
S5	0	1	0	0	0	0	0	0	—	0
S6	0	0	0	0	0	0	0	0	—	0
S7	1	0	0	0	0	0	0	0	—	0
S8	0	0	0	0	0	0	0	0	—	0
—	—	—	—	—	—	—	—	—	—	—
S40	0	0	0	0	0	0	0	0	—	0

The data in row *i* of the *Fi* adjacency matrix *F*, such as F1 is 0; *Fj* is the data in column *j* of the adjacency matrix F, F1 is 0.

2.3.2. Risk Factor Reachability Matrix Construction

The calculation method that describes the degree of reach between the features in the directed connection diagram through a certain length path based on the matrix form is called the risk factor reachable moment G [23]. The risk factor reachability matrix has an important evolutionary law property: if Si passes through a channel of unit length directly to Sk, and Sk passes through a channel of unit length directly to Sj, it means that Si must be able to Sj through a channel of two unit lengths. According to the law of progression, the adjacency matrix A of the risk factors is added to the unit matrix I, combined with the Boolean algebraic algorithm (2), and obtained by certain matrix calculus.

$$G = (F+I)^{q+1} = (F+I)^{q} \neq \cdots \neq (F+I)^{2} \neq (F+I)^{1}, q = 1,2,3\cdots \quad (2)$$

It describes the accessibility of pathways with a longitude length equal to or less than R-1 between the factors. For graphs with node factors, the longest path will certainly not exceed R-1. Where R is the order of matrix F, the tunnel fire impact factor is the total number of factors that determine whether the fire occurs or not. The reachability matrix G (Table 3) describes the degree to which a certain length of the pathway can be reached between the node factors of the directed connection graph.

Table 3. Reachability matrix *G*.

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**—**	**S40**
S1	1	1	1	1	1	1	0	1	—	0
S2	1	1	1	1	1	1	0	1	—	0
S3	1	1	1	1	1	1	0	1	—	0
S4	1	1	1	1	1	1	0	1	—	0
S5	1	1	1	1	1	1	0	1	—	0
S6	1	1	1	1	1	1	0	1	—	0
S7	1	1	1	1	1	1	1	1	—	0
S8	1	1	1	1	1	1	0	1	—	0
—	—	—	—	—	—	—	—	—	—	—
S40	1	1	1	1	1	1	0	1	—	1

2.3.3. Determine the Hierarchy of Risk Factors

On the basis of the risk factor reachability matrix, the risk factors are divided into layers, mainly using three sets X(*Fi*), Y(*Fi*), X(*Fi*) ∩ Y(*Fi*). Reachability set X(*Fi*): In the row where the factor Fi is located in the reachability matrix, the reachability matrix column element is the set of 1, representing the set of all the factors that can be reached from the factor Fi. Antecedent set X(*Fi*): In the column where the factor Fi is located in the reachability matrix, the row elements of the reachable matrix are the set of 1 s, representing the set of all the factors that can be reached from the factor Fi. X(*Fi*) ∩ Y(*Fi*), a set where the reachable set and the anterior set intersect. According to the X(*Fi*) ∩ Y(*Fi*) = X(*Fi*) conditions, the hierarchical division of risk factors is determined. In the process of hierarchical division, the risk factors of the level have been determined, the relevant rows and columns in the reachability matrix are deleted, the new reachability matrix is obtained, and the risk factors of the next level are extracted from the new matrix, and so on, until all the risk factors are completed.

According to X(*Fi*) ∩ Y(*Fi*) = X(*Fi*), such as S1 corresponding line X(*Fi*) = {1,2,8,9,10,24,28}, Corresponding columns Y(*Fi*) = {1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25, 26,27,28,29,30,31,32,33,35,36,37,38,39,40}, X(*Fi*) ∩ Y(*Fi*) = {1,2,8,9,10,24,28} = X(*Fi*), thus inferring from S1 to S40.The first condition to be satisfied is I = 1, 2, 8, 9, 10, 24, 28 which means that S1, S2, S8, S9, S10, S24, S28 is the topmost layer of the system, but also the most superficial causative factor of the tunnel fire accident, and then the elements about 1, 2, 8, 9, 10, 24, 28 are removed, and I = 3,4,5,6,25,26,27 meets the requirements, which means that S3, S4, S5, S6, S25, S26, S27 are the reasons for the second layer of the system. And so on to determine the hierarchy of risk factors.

2.4. *N-K Model Multivariate Coupling Evolution Game of Tunnel Fire*

2.4.1. Tunnel Fire Risk Factor Coupled Evolution Game

The phenomenon in which two or more forms of motion or systems interact with each other through various interactions is called coupling [24]. Tunnel fire cause system is a multi-factor coupling complex system, whether the failure of mechanical equipment can form a tunnel fire and the size of the formation of tunnel fire risk, not only by the geographical environmental factors, but also by the personnel factors, tunnel environment and operation management factors, and there is also a mutual role and influence between the five factors, that is, the multi-factor coupling effect leads to the generation and development of tunnel fire. Coupling deduction and inference are carried out on the cause factors of tunnel fire, identification and coupling analysis of fire cause factors are carried out, the frequency of causes obtained by the ISM model is used to calculate the coupling degree of the node factors of fire causes, the influence of five factors of causes on tunnel fire is analyzed, and the deep mechanism of multi-factor coupling tunnel fire occurrence is deductively reasoned, which is convenient for grasping the key points of prevention and control in the tunnel fire cause system.

Fire risk factor analysis: In tunnel fire, the ignition source and the number of combustibles are necessary factors to cause fires, and the increase in the number of combustibles and the acceleration of oxygen diffusion rate will lead to the spread and further expansion of the fire in space. Personnel will increase the risk of fire in urban tunnels due to insufficient fire fighting ability or insufficient safety quality. Combustible and flammable materials in tunnel buildings (lighting tools, high-power ventilation equipment, electrical wiring), combustibles in tunnels, and gasoline leaking in vehicles, all act as combustion mediums, added to the intensity and range of combustion, so the fire load of combustibles loaded on vehicles, flammable and explosive materials control, tunnel refractory materials, are all-powerful factors affecting the expansion of the fire. Wind currents and high temperatures in the environment fuel the fire, and the wind speed expands the fire by affecting the spread and flow of fire fumes. Analysis of the coupling mechanism of system causative factors: In tunnel fire systems, it is often difficult for a single factor to cause fire accidents. This is because the tunnel system itself has a "threshold", and the univariate system is extremely difficult to break the ring system and cause a fire. When the five subsystems of the personnel factor node, the mechanical equipment factor node, the tunnel environmental factor node, the operation management factor node, and the regional influencing factor node are coupled and oscillated, breaking the critical point of the equilibrium state, reaching the threshold that the system can accommodate leads to the coupling effect, causing the generation and expansion of fire accidents, the fire coupling mechanism is shown in Figure 3.

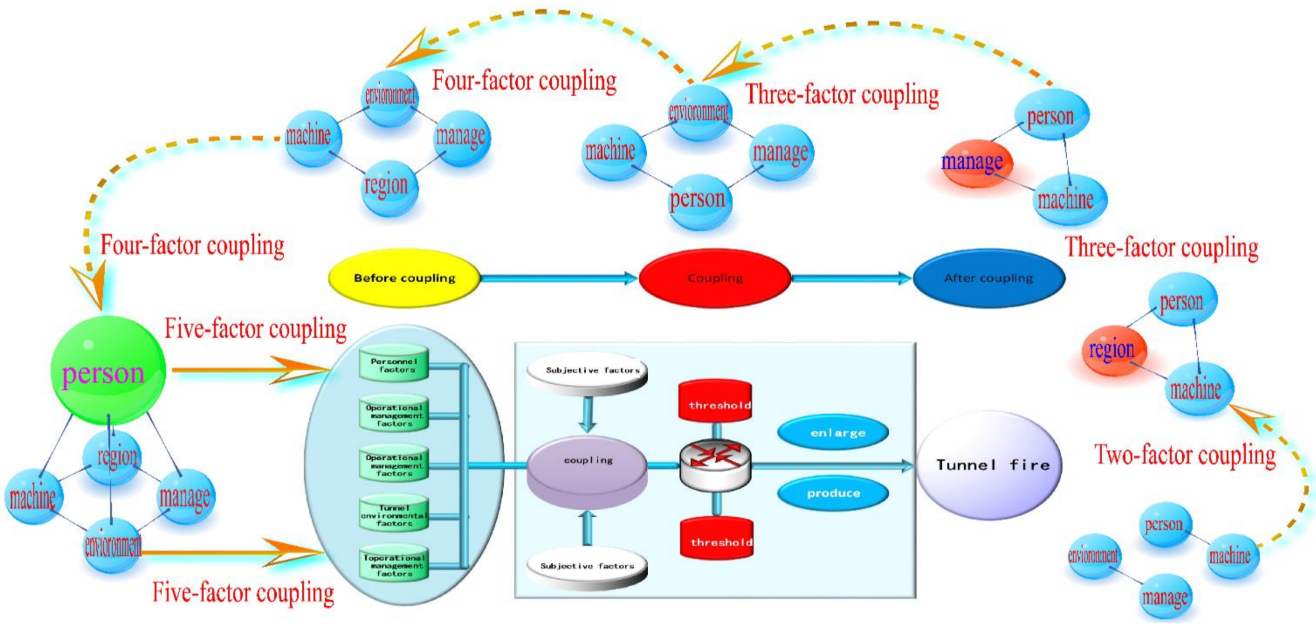

Figure 3. Multivariate coupling mechanism of tunnel fire system.

The likelihood of vehicle accidents in tunnel fire systems will vary due to population density, city size and market trade in geographical influencing factors; the emergency response ability of escape personnel will be improved by the implementation of safety management responsibility systems, safety education and publicity, and evacuation drills; and the human error of vehicle drivers will be affected by the number of tunnel lanes in the tunnel environment factors and the possibility of tunnel traffic congestion. The length and width of the tunnel in the tunnel environment will be affected by economic indicators, while the increase or decrease of traffic control will also affect the increase or decrease of the probability of vehicle accidents, and the terrain conditions will affect the size of the number of tunnel lanes.

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2.4.2. Improved Multi-Factor Coupled Calculation of N-K Mode

There are 2 parameters in the N-K model: N represents the number of nodes that make up the system, and if there are N nodes in the system, and there are n branches in each node, there are a total of nN kinds of possible combinations [25,26]. K represents the number of coupling factors related to each other in the system, with the maximum value of K being N-1 and the minimum value of 0. Coupling is divided into three categories according to the actual situation of tunnel fire.

(1) One-factor coupling. Refers to the two-by-two correlation of branch factors under a single node factor, which leads to accidents. There are five categories of univariate coupling risks, namely personnel factor node A_1, mechanical equipment factor node A_2, tunnel environmental factor node A_3, operation management factor node A_4 and geographical influencing factor node A_5, which are recorded as $T_{11}(A_1)$, $T_{12}(A_2)$, $T_{13}(A_3)$, $T_{14}(A_4)$ and $T_{15}(A_5)$.

(2) Dual factor coupling. Refers to the coupling association of two branch factors under any two node factors to cause an accident. There are 10 types of dual-factor couplingrisks, namely personnel-machinery, personnel-environment, personnel-management, personnel-region, machinery-environment, machinery-management, machinery-region, environment-management, environment-region, management-region. $T_{21}(A_1,A_2)$, $T_{22}(A_1,A_3)$, $T_{23}(A_1,A_4)$, $T_{24}(A_1,A_5)$, $T_{25}(A_2,A_3)$, $T_{26}(A_2,A_4)$, $T_{27}(A_2,A_5)$, $T_{28}(A_3,A_4)$, $T_{29}(A_3,A_5)$, $T_{210}(A_4,A_5)$.

(3) Multi-factor coupling. Refers to the occurrence of an accident in which branch factors under three or more node factors are coupled with each other. As shown in Figure 4, there are 16 types of multi-factor coupling risks, namely personnel-machinery-environment, personnel-machinery-management, personnel-machinery-region, personnel-environment-management, personnel-environment-region, personnel-environment-management-region, machinery-environment-management, machinery-management-region, machinery-management-region, environment-management-region, personnel-mechanical-environment-environment-management, personnel-mechanical-environment-region, personnel-mechanical-management-region, personnel-mechanical-management-region, Personnel-Machinery-Environment-Management-Geography. The three-factor coupling risk is $T_{31}(A_1,A_2,A_3)$, $T_{32}(A_1,A_2,A_4)$, $T_{33}(A_1,A_2,A_5)$,

$T_{34}(A_1,A_3,A_4)$, $T_{35}(A_1,A_3,A_5)$, $T_{36}(A_1,A_4,A_5)$, $T_{37}(A_2,A_3,A_4)$, $T_{38}(A_2,A_3,A_5)$, $T_{39}(A_2,A_4,A_5)$, $T_{310}(A_3,A_4,A_5)$. The four-factor coupling risk is $T_{41}(A,A_2,A_3,A_4)$, $T_{42}(A_1,A_2,A_3,A_5)$, $T_{43}(A_1,A_2,A_4,A_5)$, $T_{44}(A_1,A_3,A_4,A_5)$, $T_{45}(A_2,A_3,A_4,A_5)$, The five-factor coupling risk is recorded as $T_{51}(A_1,A_2,A_3,A_4,A_5)$.

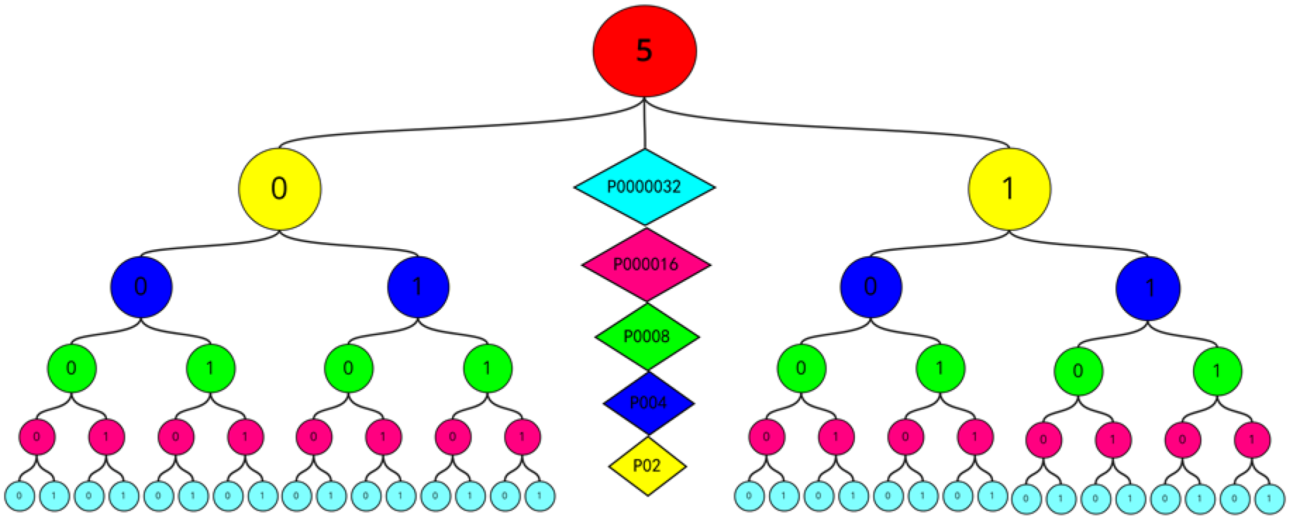

Figure 4. Multi-node factor coupling combined probability graph of tunnel fire.

The five node factors of tunnel fire are coupled to each other, and the increase in coupling frequency is related to the accumulation of coupling times, and the larger the coupling value, the higher the causal frequency. The node factor interaction coupling information is calculated as follows:

$$\begin{cases} T_{(A_1,A_2)} = \sum_{v=1}^{V}\sum_{w=1}^{W} P_{vw}\log_2\left\{\frac{P_{vw}}{P_{v....}\cdot P_{.w\cdots}}\right\}2 \\ T_{(A_1,A_2,A_3)} = \sum_{v=1}^{V}\sum_{w=1}^{W}\sum_{x=1}^{X} P_{vwx}\log_2\left\{\frac{P_{vwx}}{P_{v....}\cdot P_{.w\cdots}\cdot P_{..x.}}\right\}3 \\ T_{(A_1,A_2,A_3,A_4)} = \sum_{v=1}^{V}\sum_{w=1}^{W}\sum_{x=1}^{X}\sum_{y=1}^{Y} P_{vwxy}\log_2\left\{\frac{P_{vwxy}}{P_{v....}\cdot P_{.w\cdots}\cdot P_{..x.}\cdot P_{...y.}}\right\}4 \\ T_{(A_1,A_2,A_3,A_4,A_5)} = \sum_{v=1}^{V}\sum_{w=1}^{W}\sum_{x=1}^{X}\sum_{y=1}^{Y}\sum_{z=1}^{Z} P_{vwxyz}\log_2\left\{\frac{P_{vwxyz}}{P_{v....}\cdot P_{.w\cdots}\cdot P_{..x.}\cdot P_{...y.}\cdot P_{....z}}\right\}5 \end{cases} \quad (3)$$

where v = 0, 1, . . . , V; w = 0, 1, . . . , W; x = 0, 1, . . . , X; y = 0, 1, . . . , Y; z = 0, 1, . . . , Z, representing the state of the five factors of personnel-equipment-environment-management-region, respectively; *Pvwxyz* represents the probability of coupling between the five factors of personnel-machinery-environment-management-region in the v, w, x, y, and z states, respectively; T represents the causal frequency of node coupling, and the solution of the T value also requires the frequency of five node couplings.

$$\begin{cases} C_k^2, Single\ node\ factor\ coupling \\ \prod_{j=1}^{J} C_k^1, Multi-node\ factor\ coupling \end{cases} \quad (4)$$

where j = 1, 2, . . . , J, representing the node layer factors contained in the coupling combination, that is, the coupling factors; k = 1, 2, . . . , K, representing the branch risk factor in the node layer factors contained in the coupling combination.

According to the frequency of the node factor of the tunnel fire network, the frequency of 32 coupling conditions is solved. In the deduction of tunnel fire events, each node factor has two states, occurrence (Xi = 1) and non-occurrence (Xi = 0), then the 32 cases of tunnel fire node factor coupling are divided into different combined probabilities (Figure 4), such as single-node coupling is divided into two cases of node participation in coupling and node participation in coupling (icon P02), recorded as P0 and P1; Two-node coupling is divided into two nodes are not involved in coupling, one of the nodes participate in coupling, two nodes are involved in coupling 4 cases (icon P004), denoted as P00, P01, P10, P11; and so on, there are 8 cases of three-node coupling (icon P0008), recorded as P000, P001, P010, P011, P100, P101, P110, P111; four-node coupling has 16 cases (icon P000016), denoted as P0000, P0001, P0010, P0011, P0100, P0101, P0110, P0111, P1000, P1001, P1010, P1011, P1100, P1101, P1110, P1111; There are 32 cases of five-node coupling (icon P0000032), recorded as P00000, P00001, P00010, P00011, P00100, P00101, etc. Solve for the number of occurrences of various situations to obtain the frequency of coupling combinations.

3. Results

3.1. Building the ISM Diagram

According to the above calculation and analysis, the first level node of the cause factor of the tunnel fire accident is obtained: R1 = {1, 2, 8, 9, 10, 24, 28}, the second level node: R2 = {3, 4, 5, 6, 25, 26, 27}, the third level node: R3 = {11, 12, 13, 14, 15, 16, 17, 18}, the fourth level node: R4 = {19, 20, 21, 22, 23, 29, 32, 33, 33, 36, 37}, the fifth level node: R4 = {7,35}, level 6 node: R4 = {38,39}, level 7 node: R4 = {40,31}. R1, R2, R3, R4, R5, R6, R7 are placed in each layer, and the related factors are connected according to the logical relationship of the elements in each layer, and the structural model of the cause of tunnel fire accident is constructed.

The risk factors of the R1, R2 and R3 layers are mainly from the factors of personnel and mechanical equipment, and are also the direct cause factors of the surface of tunnel fire accidents. These 23 risk factors are shallow risk factors and direct influencing factors, which can directly cause tunnel fires, of which vehicle failure, vehicle driver human error and vehicle accidents are all high-frequency causes of tunnel fire accidents. R4 and R5 are tunnel environmental and operational management factors, which are indirect causes of tunnel fires, and these 13 risk factors are affected by changes in deeper and lower causative factors, while risking and influencing shallow risk factors. R6 and R7 are geographical influencing factors, the underlying risk factors for tunnel fire accidents, and the power system factors with higher frequency.

3.2. N-K Model Calculation Result

Combined with Figure 1f and Appendix A, the frequency of 40 risk factors in 100 tunnel fire accidents is counted, such as X_1 (vehicle driver error) appears 25 times, then P_{X1} = 25/100 = 0.2500, From this analogy from X_1 to X_{40}, the frequency of 40 risk factors leading to tunnel fires is obtained Figure 1f.

For example, in the case of single-node coupling of mechanical equipment, that is, the frequency of '01000': $P_{01000} = X_1 \times X_2 + X_1 \times X_3 + X_1 \times X_4 + X_2 \times X_3 + X_2 \times X_4 + X_3 \times X_4 = X_1(X_2 + X_3 + X_4) + X_2(X_3 + X_4) + X_3 \times X_4 = 0.0877$.

In single node factor coupling analysis, under different conditions, the frequency of single node coupling is different, known by the Formula (3), it is necessary to solve the value of $Pv \times Pw \times Px \times Py \times Pz$. Frequency P0 without the participation of personnel nodes in coupling ... = $P_{0....} = P_{00000} + P_{01000} + P_{00100} + P_{00010} + P_{01100} + P_{00110} + P_{01110} + P_{01111} = 0.8497$, the frequency of coupling with personnel nodes $P_{1....} = 1 - 0.8497 = 0.1503$. By analogy, the probability of mechanical, environmental, administrative, and regional nodes participating in the coupling conditions can be calculated. The detailed calculation results are shown in Figure 1f.

Human-mechanical two-node coupling, i.e., frequency of '11000': $P_{11000} = X_1 \times X_5 + X_1 \times X_6 + X_1 \times X_7 + X_1 \times X_8 + \ldots + X_4 \times X_5 + X_4 \times X_6 + X_4 \times X_7 + X_4 \times X_8 = (X_1 + X_2 + X_3 + X_4)(X_5 + X_6 + X_7 + X_8) = 0.1149$.

Dual-node coupling analysis. There are 10 cases of double node coupling, there are 4 different combinations in each double node coupling, and the values of *Pvw*, *Pvx*, *Pvy*, *Pvz*, *Pwx*, *Pwy*, *Pwz*, *Pxz*, *Pyz* need to be calculated first. For example, the frequency of the human node and the mechanical node is completely unaffected under coupling conditions: $P_{00\cdots} = P_{00000} + P_{00100} + P_{00010} + P_{00010} + P_{00001} + P_{00110} + P_{00011} \ldots + P_{00111} = 0.1889$. The detailed calculation results are shown in Figure 1f (*3*,*4*,*5*,*6*).

Human-mechanical-environmental three-node coupling, i.e., the frequency of '11000': $P_{11100} = X_1 \times X_5 \times X_9 + X_1 \times X_5 \times X_{10} + X_1 \times X_5 \times X_{11} + X_1 \times X_5 \times X_{12} + \ldots + X_4 \times X_8 \times X_9 + X_4 \times X_8 \times X_{10} + X_4 \times X_8 \times X_{11} + X_4 \times X_8 \times X_{12} = (X_1 + X_2 + X_3 + X_4)(X_5 + X_6 + X_7 + X_8)(X_9 + X_{10} + X_{11} + X_{12}) = 0.2623$. The same principle can be computed to solve the frequency of other coupling cases.

Multi-node coupled analysis. In the 16 cases of multi-node coupling, it is necessary to first solve the values of the five cases of three-node coupling *Pvwx*, *Pvwy*, *Pvwz*, *Pvxy*, *Pvxz*, *Pvyz*, *Pwxy*, *Pwxz*, *Pwyz*, *Pxyz* the values of the five cases of four-node coupling *Pvxyz*, *Pvwyz*, *Pvwyz*, *Pvwxy*, *Pwxyz*, *Pvwxyz case.* The detailed calculation results are shown in Figure 1f (*7*,*8*,*9*).

4. Comparative Analysis and Discussion of Model Results

According to the node factor causation frequency in Figure 1f (*2*,*3*,*4*,*5*,*6*,*7*,*8*,*9*) obtained, the substitution Formula (3) calculates the coupling causal risk values of double nodes and multiple nodes: $T_{11}(A_1) = 0.0585$, $T_{12}(A_2) = 0.0653$, $T_{13}(A_3) = 0.0517$, $T_{14}(A_4) = 0.0449$, $T_{15}(A_5) = 0.0381$ etc., and all node coupling causation risk values are analyzed together for comparison 4-4 (*10*).

From the calculation results and Figure 1f (*10*), it can be seen that the various node coupling cause risk values are sorted: $T51 > T41 > T42 > T43 > T44 > T45 > T31 > T32 > T34 > T37 > T33 > T38 > T35 > T39 > T310 > T21 > T25 > T22 > T26 > T23 > T28 > T24 > T27 > T29 > T210 > T12 > T11 > T13 > T14 > T15$.

Figure 1f (*10*) and T value ranking show that the comprehensive coupling of five-node factors has the highest probability of tunnel fire, the risk of coupling of four-node factors is greater than the risk of coupling of three-node factors, the risk of coupling of three-node factors is greater than the risk of coupling of two-node factors, and the probability of tunnel fire occurring from single-node factor coupling is the lowest, which is in line with objective laws. Among the four-node factor risk coupling, the human-mechanical-environmental-management node coupling tunnel fire accident probability is the largest, and the mechanical-environmental-management-regional node coupling tunnel fire accident probability is the smallest. From Figure 1f (*1*), it can be seen that the frequency of human error and vehicle accidents caused by vehicle drivers is high, and the frequency of risk factors under personnel and mechanical equipment factors is high, while the frequency of risk factors under operation management and geographical influencing factors is generally low.

In this paper, subjective factors refer to the subjective initiative of the driver in the driving process, such as driver human error and operation management factors; objective factors refer to the material objects that exist objectively during the driving process of the vehicle, such as mechanical equipment factors and geographical influencing factors. Incomplete coupling of personnel and operations management factors is less risky than full coupling. When the coupling factors are consistent, the mechanical equipment factor is more likely to cause a fire than the tunnel environment factor, and the personnel node is more likely to cause a tunnel fire than the operation management factor. In the double-section coupling analysis, the probability of cause of fire accidents in the coupling tunnel of personnel-mechanical equipment factors was the largest, and the probability of causes of fire accidents in the coupling tunnel of operation management-geographical influencing factors was the smallest, indicating that the coupling risk of objective factors was smaller than that of subjective factors.

From the tunnel fire accident cause ISM model (Figure 5), the tunnel fire accident cause system is a 7-level step complex structure involving surface R1, subsurface R2, final surface R3, intermediate layer R4, deep R5, deep R6 and low layer R7 accident causes, reflecting the logical relationship between accident risk factors.

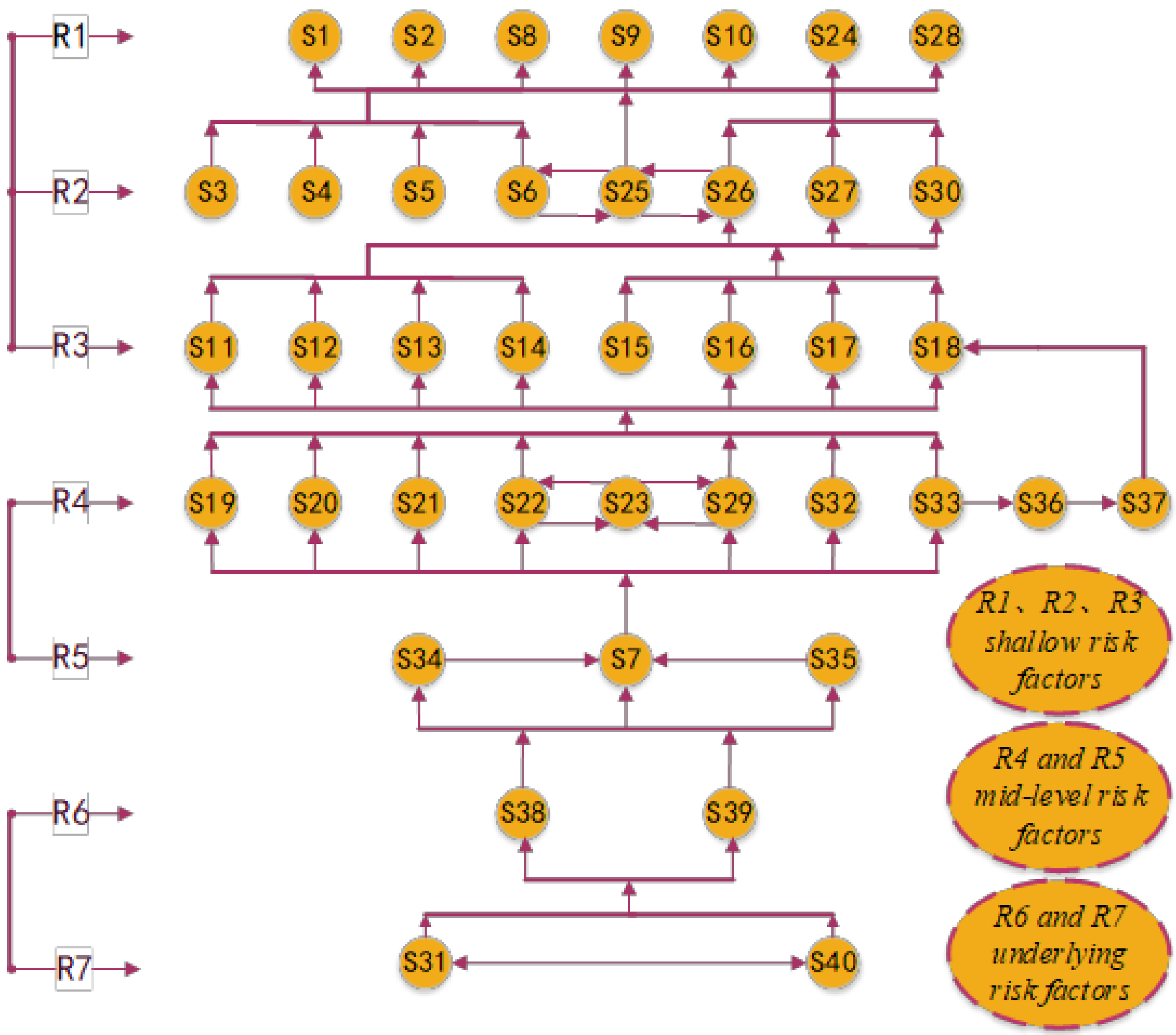

Figure 5. Tunnel fire ISM model.

In the actual accident statistics, the risk coupling frequency is equal to the ratio of the number of accidents caused by each coupling situation and the number of accidents of all accidents, the sum of the frequencies is 1, in order to facilitate analysis and comparison, the risk coupling frequency is normalized, and the frequency of each coupling situation is the sum of the frequencsies of all coupling conditions. The resulting coupling frequency and ISM accident cause analysis are compared with 100 accidents at home and abroad tunnel fire accident investigation reports and 158 tunnel fire literature for comparative analysis (Figure 6).

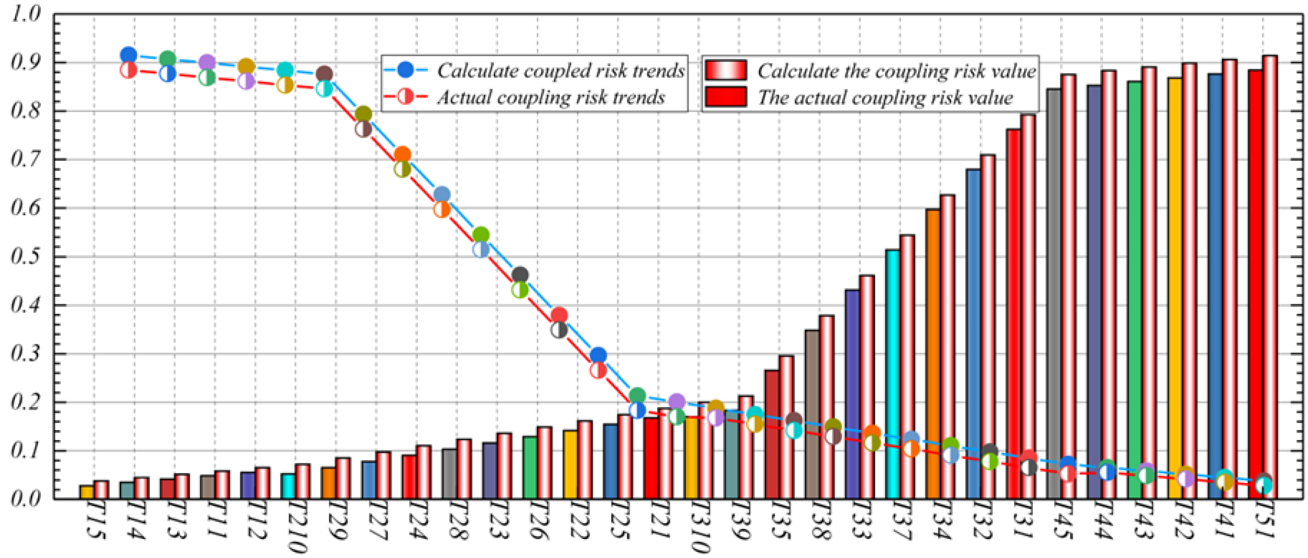

Figure 6. Calculation and actual comparative analysis chart.

From Figure 6, it is found that the ISM accident cause analysis and N-K multi-factor coupling risk value have a high coincidence with the statistical analysis of tunnel fire accidents at home and abroad, and with the increase of coupling nodes, the probability of tunnel fire accidents also shows an upward trend. In summary, the model analysis results are consistent with the research conclusions of Scholars such as Hu Jiawei [17], Kang Xiaolong [2], Lai Jinxing [27] that traffic accidents and spontaneous combustion of vehicles are the high-frequency causes of tunnel fires, and the hierarchical network model coupled with tunnel fire risks is highly consistent with the accident tunnel fire accident investigation report and the tunnel fire literature analysis. The ISM-NK analysis model is an improvement and extension of the traditional analysis method, which does not consider the interdependencies between various risk factors, and it is difficult to identify the dependence between the accident sequence and various causal factors and quantitatively evaluate the coupling relationship. The analysis of the hierarchical and coupling relationship of tunnel fire risk factors is conducive to the more effective allocation of resources by traffic and tunnel management departments and the strengthening of tunnel fire prevention [28]. In this study, the ISM-NK coupling model was able to analyze the interaction between tunnel fire risk factors while helping management identify risk focal areas and complex coupling relationships in high-risk systems, such as coal, chemical, and construction industries.

5. Conclusions

A tunnel traffic system is a complex network system composed of a variety of interrelated risk factors, tunnel fire causes can not be attributed solely to human error or equipment failure, but the result of the coupling of multiple risk factors. The joint coupling of multiple factors such as tunnel form, scale, traffic flow composition, traffic volume, tunnel management level and location area affects the frequency of tunnel fires. Therefore, the concept of the multi-factor coupled evolutionary game of tunnel fire is of great significance for analyzing the interaction between fire cause factors in a tunnel fire. After analyzing 100 tunnel fire accidents at home and abroad and 40 risk factors in 158 tunnel fire literature, a hierarchical network model for comprehensive analysis of tunnel fire risk coupling is established by using the integrated ISM-NK coupling concept. The coupling effect between different risk factors is studied, the dynamic process of tunnel fire will continue to be studied, and the coupling model of wind and fire will be established and analyzed at different scales.

(1) In total, 4 of the 40 fire cause factors (such as power system and economic indicators) are the underlying risk factors of tunnel fires, 23 of the 40 fire risk factors (such as

vehicle failure, vehicle driver human error and vehicle accidents) are shallow risk factors and direct influencing factors of tunnel fires, and 13 risk factors (such as the number of tunnel lanes, vehicle types, safety education and publicity) are indirect causes of tunnel fires. Strengthen the inspection and evaluation of tunnels to eliminate hidden dangers; increase safety education for drivers and passengers to ensure driving safety and vehicle safety; traffic and tunnel management departments to strengthen the management of tunnel equipment (such as emergency lighting systems, real-time broadcast systems), standardize operating procedures, and improve the safety management system.

(2) The frequency of tunnel fires occurring in the complete coupling of the five risk factors is the highest, the probability of tunnel fire occurrence shows an upward trend with the increase of risk factors, and the coupling risk of subjective factors (personnel and operation management factors) is higher than that of objective factors coupled (equipment factors and geographical influencing factors). This conclusion shows that the traffic and tunnel management departments have increased the control of tunnel vehicles and improved the response and handling mechanism for sudden emergencies in tunnels.

(3) The application of ISM constructs a visual multi-factor cascade model between inter-related risk factors, the NK model reveals the degree of coupling of risk factors of different coupling types, and the coupling of the ISM-NK model is more suitable for describing the complex coupling interaction between tunnel fire risk factors. Provide a theoretical basis for safety managers and decision-makers to formulate corresponding fire prevention and control measures and policies.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Statistical table of tunnel fire accidents at home and abroad.

Digit	Year	Place	Tunnel Name	Length /km	Cause of the Fire	The Degree of Tunnel Structure Breaking	Casualties	The Extent of the Damage to the Car
1	1949	American	Holland Tunnel	2.600	Cargo drops	The tunnel was seriously broken by 200 m	66 dead and 48 wounded	10 trucks and 13 cars burned down
2	1968	German	Hamburg-Morfrett Road Tunnel	0.243	The brakes of the truck carrying 14 t of polyethylene failed	The tunnel was severely damaged by 34 m	without	Damaged 1 truck, 1 trailer
3	1971	France	Klotz Tunnel l	——	——	——	Three people died	——
4	1972	Japan	Hokuriku Tunnel	——	The food truck caught fire	——	30 people were killed and 714 wounded	——
5	1974	France-Italy	Blanc Tunnel	11.600	The van engine caught fire	——	1 person was injured	——
6	1975	Spain	Guadarrama Tunnel	3.345	4 trucks and two sedans collided	Tunnel was badly broken 210 m	——	1 van was damaged
7	1976	Shaanxi	Baijiang Water Tunne	0.383	The freight train derailed and subverted, causing the tank train to explode	Baocheng Railway interrupted transportation for 382 h and 15 min	75 dead and 14 wounded	The tanker trucks were all burned down
8	1978	Netherlands	Velsen Tunnel	0.768	Cars collide	Tunnel was severely damaged by 30 m	Five people died and five were injured	6 cars were damaged
9	1979	Japan	Saka Highway, Japan Tunnel	2.045	Cars collide	Tunnel was severely damaged 1100 m and closed for 35 days	Seven people died and two were injured	Damaged cars 189 closed for 35 days
10	1979	Japan	Nihonzaka Tunnel		Cars collide	——	7 dead and 2 wounded	127 trucks and 46 cars burned down
11	1980	Japan	Kajiwar Highway Tur	0.740	The van carrying (3600 L) paint capsized	Tunnel wreaked havoc on 280 m	1 person died	2 cars damaged
12	1982	Afghanistan	salang Tunnel	2.700	(33,000 L) tanker truck collided	——	More than 700 people died	——
13	1982	American	Oakland Cacourt Tun	1.028	The truck collided with the tanker truck	Tunnel wreaked havoc on 580 m	Seven people died and two were injured	7 cars were damaged
14	1982	American	Caldecott Tunnel		Vehicle collisions	——	7 dead and 2 wounded	2 trucks and 5 cars burned down
15	1983	Italy	Pecorila Tunnel	0.662	Trailer rear-end	Tunnel was severely damaged by 200 m	9 dead and 22 wounded	10 cars burned down
16	1984	Switzerland	Gotthard Tunnel	12.320	Trucks burn	Tunnel was badly damaged by 30 m		Damaged 1 van
17	1984	Austria	Fairbertau Tunnel	5.130	The bus was on fire	Tunnel top lining and equipment 100 m		Damaged 1 bus
18	1986	France	L'aime Tunnel	0.662	Trailer rear-end	Some of the devices inside the Tunnel were destroyed	3 dead and 5 wounded	5 cars were damaged

Table A1. *Cont.*

Digit	Year	Place	Tunnel Name	Length /km	Cause of the Fire	The Degree of Tunnel Structure Breaking	Casualties	The Extent of the Damage to the Car
19	1987	Switzerland	gumefens	0.343	3 trucks and 5 cars collided	Minor damage	2 deaths	3 vans were damaged
20	1990	Norway	Rldal Tunnel	4.656	Vans collide	Minor damage	1 person was injured	
21	1990	France-Italy	Blanc Tunnel	11.600	The van engine caught fire	Some of the devices inside the Tunnel were destroyed	2 people were injured	1 car was damaged
22	1991	Guangdong	Dayao Mountain Tunnel	1.429	——	——	12 dead and 20 wounded	——
23	1993	Shaanxi	Lin Jia Chuan Tunnel	13.618	——	——	8 dead and 10 wounded	——
24	1993	Italy	Serra Ripoli Tunnel	0.442	Vans collide	Minor damage	4 dead and 4 wounded	16 cars were damaged
25	1993	Norway	Hovden Tunnel	1.290	Motorcycles collide	Tunnel was badly damaged by 111 m	Five people were injured	Loss of 1 motorcycle and 2 cars
26	1994	South Africa	Huguenot Tunnel	3.914	The bus motor malfunction caught fire	——	1 dead and 28 wounded	1 bus was destroyed
27	1995	Austria	Pfander Tunnel	6.719	Vans collide	Serious damage	3 people died	Damaged 4 cars
28	1996	Italy	Palemo Tunnel	0.148	Tanker truck exploded	Days of severe destruction, closed for 2.5 days	5 dead and 26 wounded	19 cars were damaged
29	1996	England	The Anglo-French Undersea Tunnel	——	——	——	36 people were injured	——
30	1999	Italian-French ju	Mont Blanc Tunnel	——	Spontaneous combustion of cars	——	44 people died	34 cars burned down
31	1999	Austria	Tauern Tunnel	——	Vehicle collisions	——	12 people died	34 vehicles burned down
32	1999	Italian-French junction	Mont Blanc Tunnel	11.600	Trucks burn	Concrete dome all desertification fire spread 1.2 km, the highest temperature of 1000 °C closed for nearly 3 years	41 people died	43 cars were damaged
33	1999	Austria	Thorn Highway Tunn	6.400	Cars collide (1 van loaded with paint)	The maximum temperature is 1200 °C The 600 m Tunnel collapsed	Thirteen people died	34 cars were damaged
34	2000	Norway	Seljestad Tunnel	1.272	Vans collide	Tunnel is closed for 2 days	Six people were injured	Eight cars were damaged
35	2000	Austria	Horn Hill Tunnel	——	——	——	155 dead and 18 wounded	——
36	2001	Zhejiang	Cat Beaver Ridge Highway Tunnel	3.590	Trucks burn	The overall strength was not greatly affected	There were no casualties	Traffic was disrupted for 18 days
37	2001	Switzerland	St. Gotthard Tunnel	——	Van collision	——	11 deaths	13 trucks and 10 cars burned down

Table A1. *Cont.*

Digit	Year	Place	Tunnel Name	Length /km	Cause of the Fire	The Degree of Tunnel Structure Breaking	Casualties	The Extent of the Damage to the Car
38	2001	Henan	Amber Hill Tunnel	0.500	Trucks burn	Tunnel was out of service for 10 days		Damaged 1 van
39	2001	Switzerland	Gotthard Tunnel	16.918	Vans collide	Tunnel roof collapsed large blocks for a long time	11 deaths	23 cars were damaged
40	2001	Italy	Prapontin Tunnel	4.409	Mechanical failure	Tunnel is closed for 10 days	Nineteen people were injured	——
41	2001	Austria	Gleinalm Tunnel	8.320	Vans collide	——	5 people died	Loss of 2 cars
42	2001	Denmark	Guldborg Tunnel	0.460	1 van and several cars chased after the fire	——	5 dead and 4 wounded	——
43	2002	Zhejiang	Cat Beaver Ridge Tunnel	3.616	The engine caught fire	About 200 m of the tunnel was damaged, the walls were peeled off, and the facilities were severely paralyzed		1 large truck burned down
44	2003	Korea	Seoul Hongzhimen Tu	1.890	Cars collide	——	More than 30 people were injured	Damaged one bus, 1 car
45	2004	Zhejiang	Cat Beaver Ridge Tunnel	3.616	Damag de Onabas, 1 card	——	1 person was injured	Six cars collided end-to-end, and three of them were burned
46	2004	Zhejiang	YongtaiWen Niu Guantou Tunnel		Carrying 50 t of calcium carbide Damag de Onabas, 1 card	——	——	Vehicles burned down
47	2005	Franco-Italian border	Ferreris Highway Tun	12.8000	Trucks burn	Closed for 14 months	2 dead and 20 wounded	Several cars were damaged
48	2005	Sichuan	Dong Jiachuan Tunne	——	Gas exploded	——	44 dead and 11 wounded	
49	2005	Zhejiang	Niuyanling Tunnel	——	Caused by a crash	The tunnel structure was slightly damaged	Multiple people were injured	The vehicle caught fire
50	2005	Chongqing	Masatakeyama Tunne.	——	Damag de Onabas, 1 card	——	——	Vehicles burned down
51	2005	Fujian	Fly twin ridge Tunnel	——	The brakes failed and the wheels caught fire	——	Eight people were injured	1 bus burned down
52	2006	Gansu	Ring River Tunnel	0.485	Cars collide	About 9 t of cargo were all burned	1 dead and 4 wounded	2 trucks burned down

Table A1. *Cont.*

Digit	Year	Place	Tunnel Name	Length /km	Cause of the Fire	The Degree of Tunnel Structure Breaking	Casualties	The Extent of the Damage to the Car
53	2006	Zhejiang	Four-cornered pointed Tunnel	——	The engine spontaneously combusts	Caused by the fire can not pass, part of the mechanical and electrical equipment and lining damage	——	——
54	2006	Zhejiang	Wenzhou Tianchangling Tunnel	——	Damag de Onabas, 1 card	The Tunnel structure was slightly damaged	——	The vehicle caught fire
55	2006	Switzerland	A13 Weimara Tunnel	——	Rear-end	6 dead and 6 wounded	——	1 bus, 2 cars were burned down
56	2006	Zhejiang	Yongtaiwen Matunling Tunnel	——	Damag de Onabas, 1 card	——	——	Vehicles burned down
57	2006	Guizhou	Songzun Expressway Songkan Tunnel		The wall of the car caught fire	——	——	Vehicles burned down
58	2006	Guangzhou	Luochang Expressway Yangmenling Tunnel		The engine spontaneously combusts	The tunnel cable was burned	——	1 van was burned down
59	2006	Guangzhou	Hot spring tunnel	0.405	The tires of the van burst and caught fire	Tunnel lighting equipment and fire protection layers were severely damaged	——	The van burned down
60	2006	Zhejiang	Hongyan Tunnel in Qinshun County, Wenzhou	——	Damag de Onabas, 1 card	——	——	Vehicles burned down
61	2007	America	Interstate Tunnel No.	——	15 trucks and 1 car collided in a row	——	3 dead and 10 wounded	Vehicles burned down
62	2007	Shenzhen	Tanglang Shan Tunne	——	——	——	——	——
63	2007	Sichuan	Yusui High-Speed Tu		Buses spontaneously combust			Vehicles burned down
64	2007	Chongqing	Dabaoshan Tunnel	3.875	Buses spontaneously combust	Tunnel lighting exhaust cable burned out	Six people were injured	1 minibus burned down
65	2008	Guangdong	Dabaoshan Tunnel	3.150	Xylene leaks and burns violently	The cement steel bar fell off and was closed for more than 1 month for maintenance	2 deaths	Vehicles burned down

Table A1. *Cont.*

Digit	Year	Place	Tunnel Name	Length /km	Cause of the Fire	The Degree of Tunnel Structure Breaking	Casualties	The Extent of the Damage to the Car
66	2008	Shaanxi	Baocheng Railway 109 Tunnel	——	earthquake	The tunnel is damaged	2 people were injured	——
67	2008	Guangdong	Jingzhu Dabaoshan Southbound Tunnel	——	Trailer rear-end	——	2 dead and 5 wounded	——
68	2009	Shaanxi	Qinling-Zhongnanshan Tunnel	——	The van caught fire	The Tunnel is closed for 1 h	——	——
69	2010	Zhejiang	Daxiling Tunnel	4.116	Semi-trailer tires caught fire	Mechanical and electrical facilities were damaged and traffic was interrupted for 7 h		9 cars burned down
70	2010	Jiangsu	Wuxi Huishan Tunne	——	Buses spontaneously combust	——	24 dead and 19 wounded	The bus burned down
71	2010	Fujian	Xiamen Xiang'an Tur	——	The van spontaneously combusted	The tunnel is closed for several hours	——	——
72	2010	Slovenia	Trojane Tunnel	——	Spontaneous combustion of cars	——	Five people were injured	——
73	2011	Shenyang	Ningde Fei Twin Ridge Tunnel	——	Rear-end of 4 sedans	Rear-end of 4 sedans	1 person was injured	3 cars caught fire
74	2011	Gansu	New Seven Beam Tunnel	4.010	2 tanker trucks rear-ended	The entire tunnel circuit was paralyzed, and a large number of facilities were damaged to the tunnel structure and road surface	4 dead and 1 wounded	3 cars burned down
75	2013	Gansu	Taohuagou Tunnel	0.439	2 car rear-end, 30 t nitrobenzene deflagration	The tunnel vault burned, the concrete peeled off in a large area, and closed for 6 h	Three people were injured	1 semi-trailer burned down
76	2013	Hubei	Jijiapo Tunnel	3.584	The tire caught fire	——	——	22 new cars burned down
77	2014	Guizhou	Jatopo Tunnel	——	Trailers spontaneously combust	30 t of cargo burned		1 trailer burned down
78	2014	Fujian	Fly Twin Ridge Tunnel	——	2 trucks and 1 sedan rear-end	——	——	3 cars burned down
79	2014	Shanxi	Tunnel behind the rock	0.786	Methanol car rear-end	The concrete fell off at 3 points of the tunnel	31 people died and 9 people are missing	42 vehicles burned down
80	2015	Guangzhou	Guanghe Expressway Phoenix Mountain Tunnel	——	6 cars collided and 2 cars caught fire	——	——	2 cars caught fire and destroyed

Table A1. *Cont.*

Digit	Year	Place	Tunnel Name	Length /km	Cause of the Fire	The Degree of Tunnel Structure Breaking	Casualties	The Extent of the Damage to the Car
81	2015	Henan	Archaeopteryx Tunnel	——	Cars spontaneously combust	——	——	2 cars caught fire and destroyed
82	2017	Hubei	Jijiapo Tunnel	3.854	Damag de Onabas, 1 card	——	——	22 new cars burned down
83	2017	Shandong	Weihai High-Speed Tunnel	——	Artificial arson	——	12 people died	1 school bus burned down
84	2017	Hebei	Zhangshi High-Speed Tunnel	——	Vehicle deflagration	The tunnel is closed to vehicle congestion for 14 km	12 people died	1 car burned down
85	2018	Zhejiang	Zhoushan East Tunne	——	——		——	——
86	2019	Zhejiang	Xueling Tunnel	——	Trains spontaneously combust	——	——	——
87	2019	Yunnan	Tashi Tunnel	——	Gas disaster	The tunnel was on fire	2 dead, 2 wounded and 5 missing	9 cars damaged
88	2019	Zhejiang	Cat Beaver Ridge Tunnel	3.616	The tire caught fire	The tunnel was on fire	5 dead and 31 wounded	400 cars were damaged
89	2020	Hunan	Snow Peak Mountain Tunnel	——	The semi-trailer caught fire	The tunnel was on fire	65 people were trapped	33 cars stranded
90	2020	Fujian	Yudun Tunnel	——	The trolley caught fire	——	People are trapped	A large number of vehicles are stranded
91	2020	Guangdong	Prayer Tunnel	——	The front of the truck caught fire	——	——	——
92	2020	Wuhan	Yangtze River Tunnel	——	The van caught fire	——	——	——
93	2021	Yunnan	Daguan County Tunn	——	Bus rear-end	The fire spread	75 people were trapped and 4 were injured	2 cars burned down
94	2021	Shanghai	Hongqiao South Tunn	——	——	——		1 cars burned down
95	2021	Guangxi	Lan Chong Tunnel	——	Cargo on fire	The tunnel was on fire	——	The van burned down
96	2021	Fujian	Luohan Mountain Tu	——	Vehicle rear-end	——	4 people trapped 30 injured	2 cars burned down
97	2021	Hunan	Jiahu Tunnel	——	——	Tunnel congestion	——	——
98	2021	Gansu	Dawu Tunnel	——	The van caught fire	Traffic disruptions	——	——
99	2021	Guizhou	Seven Star Pass Tunnel	——	The van caught fire	The tunnel was on fire	69 people were trapped	1 cars burned down
100	2021	Zhejiang	Cat Beaver Ridge Tunnel	3.616	Trailer rear-end	The tunnel was on fire	5 dead and 36 wounded	2 cars burned down

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