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Research Article

A Novel Method for Risk Assessment of Cable Fires in Utility Tunnel

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Given the flammability of power cables and the high cost of utility tunnel construction, power cable fires cause serious economic losses and are associated with a negative social impact. In the study, a weighted fuzzy Petri net and an event tree are combined to propose a quantitative evaluation method to mitigate cable fire risks in a utility tunnel. First, cable fire risk factors are analyzed. Given the lack of utility tunnel cable fire historical data, fuzzy theory is used to calculate the failure probability of the primary event. Second, a weighted fuzzy Petri net is used for fuzzy reasoning, and an event tree is used to analyze all possible consequences. Subsequently, the numerical simulation method is used to quantify the loss from the cable fire and thereby quantify the risk of cable fire. Finally, the effect of different risk factors on a cable fire is analyzed to determine the main factors that affect cable fires. Simultaneously, the control ability of different control measures with respect to the fire is analyzed to determine key control measures. A case study of a utility tunnel cable cabin in Liupanshui in Guizhou is employed to validate the utility of the proposed method.

1. Introduction

Given the rapid development of cities, explosive growth of urban populations, and the demand for urban aesthetics, cables that were previously erected over the city and pipes within cities are no longer acceptable. The use of underground space satisfies the needs of the abovementioned urban development [1]. Utility tunnels were constructed approximately two centuries ago to solve urban water supply and sewer system problems [2]. Currently, the utility tunnel essentially corresponds to a system that incorporates some or all of the electric power, telecommunication, gas, water supply and other municipal cables and pipelines and monitoring equipment [3]. However, several pipelines and cables are placed in a utility tunnel, which can result in many hidden hazards. These hazards include gas leaks and explosions, water pipe leaks and rupture, and cable fires [4, 5]. Among them, the cable in a cable cabin is extremely likely to cause a fire in the working process, and the consequences are extremely serious. First, laying wires together in a cable rack without air space for ventilation and heat dissipation can produce a fire risk due to radiation and thermal conservation. Second, cable burning emits excessive black smoke and toxic gases, which can significantly affect fire rescue. Finally, given the narrow space of the utility tunnel, the temperature can increase rapidly within a few minutes, and firefighters are not able to perform fire-fighting operations normally [6, 7]. Therefore, it is important to adopt reasonable measures to control cable cabin fires to strengthen the management of utility tunnels.

Although cable fire risks of utility tunnels cannot be eliminated, preventive and mitigative measures can be adopted to reduce the occurrence probability and consequent severity of fire accidents. Risk analysis is an efficient tool to identify risk factors and develop strategies to prevent accidents and includes three steps: hazard identification, frequency analysis, and consequence analysis [8]. Currently, a few studies provide a basis for the risk analysis of utility tunnel cable fire. First, the main mechanisms of cable fires include arc faults, cable core overheating, and external heating [9, 10]. Subsequently, a few studies conducted detailed research on the specific factors of the cable ignition mechanism [11, 12]. Second, probabilistic simulations are performed via the Monte Carlo technique and fire dynamics simulator (FDS) as a deterministic fire model [13]. Monte Carlo simulation and CFAST are used to estimate the failure probability of redundant cables in a cable tunnel fire and failure and smoke filling probabilities in an electronics room during an electronics cabinet fire [14]. Finally, the heat release rate and toxicity of combustion products, smoke yield, and flashover category assess the effect of the mutual spacing between the cables and thermal conductivity of cable materials on fire risk [15]. Van Weyenberge et al. [16] used smoke spread, evacuation, and consequence model to determine final consequences, and the final risk was given by the expected number of fatalities, individual risk, and societal risk. The aforementioned studies provide a basis to examine utility tunnel cable fires. However, the above researches mainly focus on the mechanism of cable fire, the influence of cable parameters on fire, and the consequences of cable fire, and the risk analysis involving comprehensive causes and consequences of utility tunnel cable fires is not mentioned.

A few risk quantitative analysis methods provide ideas for solving the above problems including the Bayesian network, evidence theory, and Petri nets. However, the Bayesian network relies on historical data while performing probability updates [8, 17]. Evidence theory exhibits complexity in dealing with high-conflict evidence [18]. Furthermore, Petri nets indicate the causal relationship of fire development via places, transitions, and directed arcs. With the extension of research, studies improved Petri nets and used them in several fields such as timed Petri net (TPN), colored Petri net (CPN), and weighted fuzzy Petri net (WFPN) [19–21]. By weighing different indictors and integrating the fuzziness of information into Petri nets [22], weighted fuzzy Petri nets can not only take into consideration the importance and independence of the indicators but also be suitable for the reasoning with incomplete data.

The existing research lacks whole process risk reasoning of utility tunnel cable fires and historical data on utility tunnel cable fires. In the study, a weighted fuzzy Petri net is used to simulate a complex cable fire process. Fuzzy set theory is combined with multiexpert analysis to derive the fuzzy probability of a primary event to resolve the lack of statistical failure probability. In addition, under the influence of different control measures, the event tree is used to classify the consequences of a fire, and a numerical simulation is applied to quantify the specific accident losses of cable fires. This paper proposes a novel method for risk assessment of cable fires in the utility tunnel. A risk analysis of cable fire for the utility tunnel is conducting through this method, and the evolution process of the cable fire failure accident from causes to consequences is also presented explicitly. Essentially, the study can provide a powerful support for safety management of the utility tunnel. The rest of the study is organized as follows: A brief description of risk analysis basics including weighted fuzzy Petri nets, event trees, and fire simulators is presented in Section 2. The main steps of fire risk assessment are given in Section 3. Section 4 gives the application of weighted fuzzy Petri nets and event trees in the risk assessment of utility tunnel cable fires, and the conclusion is presented in Section 5.

2. Methodology

2.1. Weighted Fuzzy Petri Net. The Petri net was proposed by Professor Petri and exhibits significant advantages in describing system concurrency, asynchronous, distribution, parallelism, and uncertainty. The weighted fuzzy Petri net consists of a Petri net and fuzzy logic and weighting factors and is formally defined as a 10-tuple as follows [23]:

$$\text{WFPN} = \{P, T, I, O, D, M, U, R, \alpha, W\}, \tag{1}$$

where

$P = \{P_1, P_2, \ldots, P_n\}$ denotes a finite set of places. $T = \{t_1, t_2, \ldots, t_m\}$ denotes a finite set of transitions. I: $P \longrightarrow T$ denotes the input function, a mapping from places to transitions:

$$I = \{\beta_{ij}\} = \begin{cases} \beta_{ij} = 1, & p_i \text{ is input of } t_j, \\ \beta_{ij} = 0, & p_i \text{ is not input of } t_j. \end{cases} \tag{2}$$

O: $T \longrightarrow P$ denotes the output function, a mapping from transitions to places:

$$O = \{\beta_{ij}\} = \begin{cases} \beta_{ij} = 1, & p_i \text{ is output of } t_j, \\ \beta_{ij} = 0, & p_i \text{ is not output of } t_j. \end{cases} \tag{3}$$

$D = \{d_1, d_2, \ldots, d_n\}$ denotes a finite set of propositions. $|P| = |D|$.

M denotes a marking of the WFPN. $M = (\alpha(p_1), \alpha(p_2), \ldots, \alpha(p_n))^T$, and the initial marking is denoted by M_0, and αp_i denotes the truth value in place p_i.

U: $T \longrightarrow P$ denotes an association function, a mapping from transitions to real values between zero and one. $U = \{\mu_{ij}\}$, $j = 1, 2, \ldots, m$; $i = 1, 2, \ldots, n$, where μ_{ij} denotes the certainty factor of transition t_j for output place p_i.

R: $P \longrightarrow D$ denotes an association function, a bijective mapping from places to propositions.

α: $P \longrightarrow [0, 1]$ denotes an association function, a mapping from places to real values between zero and one.

W: $P \longrightarrow T$ denotes an importance function of places that reflects the degree of support of the premise proposition in the rule. $W = \{w_{ij}\}, i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$, where w_{ij}denotes the weight of place p_i for transition t_j.

2.2. Event Tree Analysis. Event tree analysis (ETA) is an inductive reasoning analysis method that is a possible consequence of inferring from the initial event in the chronological order of accident development. The construction of the event tree begins from an initiating event.

The analysis is extensively used in risk and safety analyses in several different industries. Five basic steps are used to develop an event tree as follows [24, 25]: identifying the initiating event, determining countermeasures, building the event tree, evaluation of the tree, and risk classification.

2.3. Fire Simulator. Specifically, FDS corresponds to software that is specifically designed for fire dynamic simulation and can be used to simulate low-speed transmission of fire heat and combustion products, material pyrolysis, flame propagation and fire spread, water spray, temperature detectors, and smoke detector activation. It is widely used in practice. For example, Audouin et al. [26] analyzed combustion with FDS and compared it with experimental data. Niu and Li [7] used FDS to simulate the fire temperature and smoke distribution of cable tunnel cables and verified the applicability of FDS to simulate the temperature distribution after fire combustion accurately [27].

3. Risk Assessment Method Based on WFPN-ETA

In a typical quantitative risk analysis methodology, four steps are involved: hazard identification, frequency analysis, consequence analysis, and risk quantification [8]. In this study, the risk analysis framework of the utility tunnel cable fire is proposed in combination with the characteristics of the utility tunnel cable cabin, as shown in Figure 1. First, the necessary information regarding the objective utility tunnel cable cabin is collected to determine failure modes, risk factors, and clear causal relationships. Second, primary event probability is obtained and risk reasoning using WFPN. Third, we analyze the possible outcomes of the accident sequence resulting from the initialing events. We calculate the associated consequence probabilities based on the ETA method. Finally, we use FDS to quantify risk loss, conduct risk assessment, make risk decisions, and develop control measures.

3.1. Calculation of a Fuzzy Probability. To evaluate the failure probability of the top event in a weighted fuzzy Petri net, it is necessary to determine the probabilities of the primary events in advance. However, it is difficult to obtain detailed statistical probability data of primary events; hence, a fuzzy method that consists of three steps is proposed, as shown below [28]:

Step 1. Collect a natural linguistic expression of a risk factor status.

The expert's language description of the primary events is divided into five levels: very low (VL), low (L), medium (M), high (H), and very high (VH). Simultaneously, given the different opinions given by experts, a multiexpert scoring method is frequently recommended. The expert opinion is integrated using the linear pooling method proposed by Clemen and Winkler [29], given in the following equation:

$$f_i = \sum_{j=1}^{n} W_{ej} A_{ij}, \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n, \tag{4}$$

where f_i denotes the integrated fuzzy number of event i, W_{ej} denotes the weight of expert j, A_{ij} denotes the fuzzy number for event i given by expert j, m denotes the total number of events, and n denotes the total number of experts

Step 2. Convert the natural linguistic expression to a fuzzy number.

A numerical approximation approach was proposed by Chen et al. [30], to convert the linguistic expression to a corresponding fuzzy number. Fuzzy numbers are expressed via fuzzy membership functions. Furthermore, triangular and trapezoidal fuzzy membership functions are generally preferred in fuzzy theory. In this study, the triangular fuzzy membership is used. The corresponding membership function is given in the following equation:

$$f_A = \begin{cases} 0, & 0 \le a_1, \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 < x \le a_2, \\ \dfrac{x - a_3}{a_2 - a_3}, & a_2 < x \le a_3, \\ 0, & x \ge a_3, \end{cases} \tag{5}$$

where a_1 denotes the lower bound coordinate of the triangular fuzzy number, a_2 denotes the intermediate coordinate, and a_3 denotes the upper bound coordinate.

Figure 2 establishes a membership function that is compatible with the expert linguistic variables.

Step 3. Convert the fuzzy number to a failure probability.

The method of converting the fuzzy number to a failure probability consists of the following two parts: the preferred method of transforming a fuzzy number to a fuzzy possibility score denotes the maximizing set and a minimizing set method proposed by Chen [31]. A fuzzy possibility score is defined as follows:

$$F_M = \frac{\sup\left[f_M(x) \Lambda f_{\max}(x)\right] + 1 - \sup\left[f_M(x) \Lambda f_{\min}(x)\right]}{2}, \tag{6}$$

where $f_{\max}(x)$ and $f_{\min}(x)$ represent the fuzzy maximizing and minimizing sets, respectively, and are defined as follows:

$$f_{\max}(x) = \begin{cases} x, & 0 \le x < 1, \\ 0, & \text{otherwise}, \end{cases} \tag{7}$$

$$f_{\min}(x) = \begin{cases} 1 - x, & 0 \le x < 1, \\ 0, & \text{otherwise}. \end{cases} \tag{8}$$

The fuzzy possibility score is converted to a failure probability by the empirical equation proposed by Onisawa [32, 33] as follows:

$$F = \begin{cases} \dfrac{1}{10^k}, & F_M \ne 0, \\ 0, & F_M = 0, \end{cases} \tag{9}$$

$$k = \left(\frac{1 - F_M}{F_M}\right)^{1/3} \times 2.301. \tag{10}$$

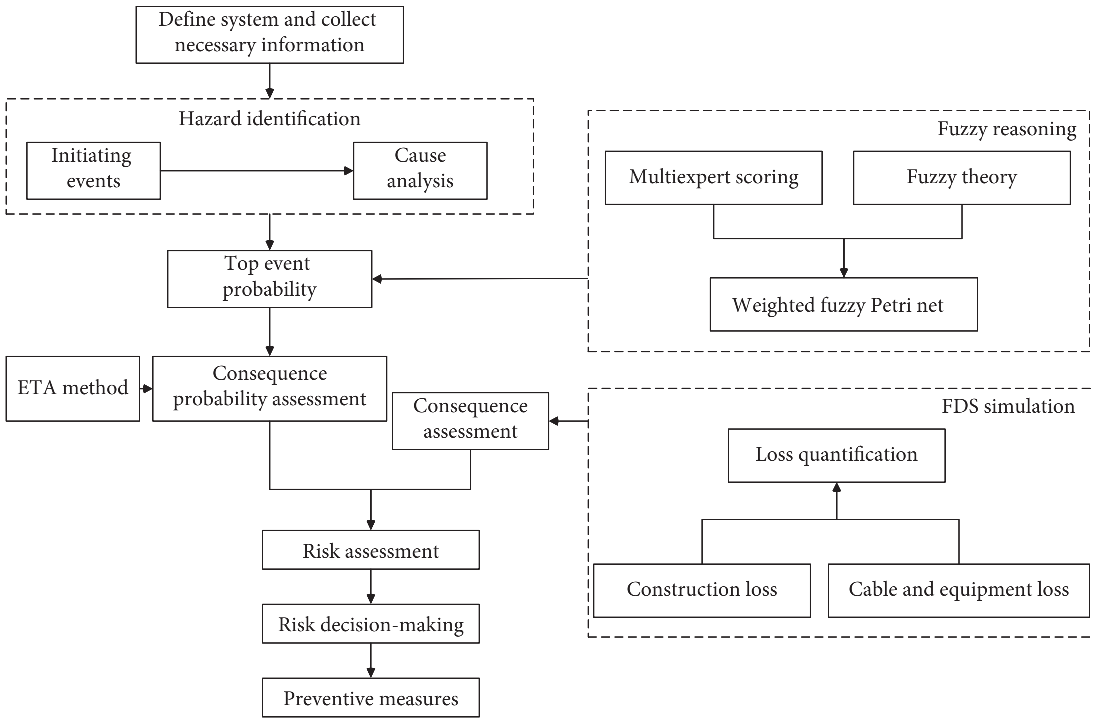

FIGURE 1: Flow chart of utility tunnel cable fires risk analysis.

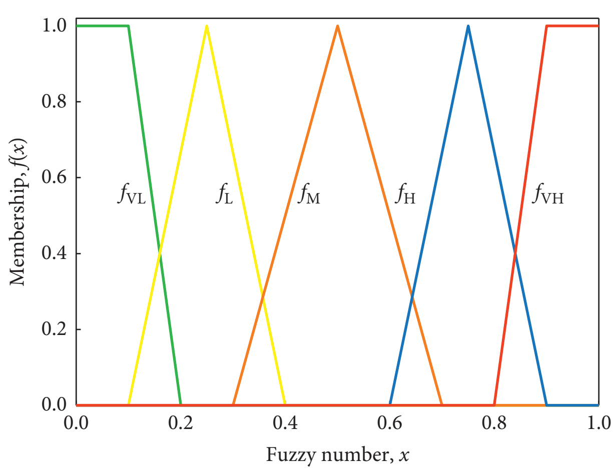

FIGURE 2: Relationship between membership function and linguistic variables.

3.2. Fuzzy Reasoning Based on WFPN

3.2.1. Logical Relationships among Risk Factors. Most knowledge in human society exhibits obvious ambiguity and uncertainty. Fuzzy production rules are used to represent inexact knowledge and fuzzy reasoning. In security risk assessment, logical relationships among risk factors are transformed into the relationships of transitions and places of WFPN. There are two basic relationships of the production rules ("AND" and "OR") in the hierarchical risk assessment as follows [21]:

The "AND" rule is as follows:

If $d_1(\alpha_1, w_1)$ and $d_2(\alpha_2, w_2)$ and $\cdots$ and $d_k(\alpha_k, w_k)$, then $d_g(\text{CF} = \mu)$; thus,

$$\alpha = \sum_{i=1}^{k} \alpha_i \times w_i \mu. \tag{11}$$

The "OR" rule is as follows:

If $d_1(\alpha_1)$ or $d_2(\alpha_2)$ or $\cdots$ or $d_k(\alpha_k)$, then $d_g(\text{CF} = \mu_1, \mu_2, \ldots, \mu_k)$; thus,

$$\alpha = \max(\alpha_i \times \mu_i), \tag{12}$$

where $\mu, \mu_1, \mu_2, \ldots, \mu_k$ are fuzzy numbers defined in the universe of discourse [0,1] that indicate the certainty factor (CF) of the rule.

3.2.2. WFPN Reasoning Process. Weighted fuzzy Petri nets use matrix inference algorithms to completely utilize the parallel processing capabilities of Petri nets to simplify the reasoning process. Prior to introducing the matrix inference algorithm, we define two matrix operators.

(1) $\oplus : Z = X \oplus Y$, where X, Y, and Z all correspond to $n \times m$ matrices, and x_{ij}, y_{ij}, and z_{ij} are their elements, respectively, such that the following expression holds:

$$z_{ij} = \max(x_{ij}, y_{ij}), \quad i = 1, 2, \ldots, n; \; j = 1, 2, \ldots, m. \tag{13}$$

(2) $\otimes : Z = X \otimes Y$, where X denotes a $n \times p$ matrix, Y denotes a $p \times n$ matrix, and Z denotes a $n \times m$ matrix, and x_{ik}, y_{kj}, and z_{ij} denote their elements, respectively, such that the following expression holds:

$$z_{ij} = \max_{1\le k\le p} \left(x_{ik} \times y_{ki}\right), \quad i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m. \tag{14}$$

As previously defined, W and U correspond to $n \times m$-dimensional matrices; M_0 that denotes the initial marking of the WFPN model corresponds an $n \times 1$-dimensional matrix. In addition, $W = \{w_{ij}\}$ denotes the weight matrix of places for transitions, where w_{ij} denotes the weight of place P_i for transition t_j if place P_i denotes the input place of transition t_j. If place P_i does not correspond to the input place of transition t_j,then $w_{ij} = 0$.

Specifically, U denotes the certainty matrix of the transitions for their outputs:

$$U = \{u_{ij}\}, \tag{15}$$

where u_{ij} denotes the certainty factor of transition t_j for the output place P_i. If place P_i does not correspond to the output place of transition t_j, then $u_{ij} = 0$.

Thresholds of transitions are not considered in the study based on the algorithms given by Liu et al. [34]. The security risk reasoning process is given as follows:

Step 1. Initialization. Establish the matrixes M_0, W, and U

Step 2. Compute the vector of equivalent fuzzy truth values of the transitions as follows:

$$\Gamma_{k+1} = W^T \times M_k. \tag{16}$$

Step 3. Compute new marking M_{k+1} as follows:

$$M_{k+1} = M_k \oplus \left(U \otimes \Gamma_{k+1}\right). \tag{17}$$

Step 4. Let $k = k + 1$, repeat steps 2 and 3 until $M_{k+1} = M_k$, i.e., the credibility of all propositions no longer changes, and the reasoning ends.

3.3. ETA-Based Accident Scenario Reasoning. In event tree reasoning, the event tree is built from an initiating event. Based on whether the next event from the chain occurs or not, the main branch splits into two branches. Each of these splits into two new branches based on whether the third event occurs. The process continues until all events from the chain are considered. The probability of a particular state is equal to the probability of the path leading to the state. The probability is determined as a product of the probabilities of the branches that comprise of the path and probability or frequency of the initiating event [25], as shown in Figure 3.

3.4. Risk Assessment

3.4.1. Risk Concept. There is no agreed definition of the concept of risk. An examination of the literature indicates a number of different methods to understand the risk concept. Risk corresponds to the probability of an undesirable event [35]. Furthermore, risk denotes a measure of the probability and severity of adverse effects [36]. Risk is also a function of the state and time of an event [37].

The combustibles in the utility tunnel mainly correspond to cables and electrical equipment. Simultaneously, the heat released by the fire and high-temperature flue gas generated affect the concrete of the utility tunnel, and the cable fire risk formula of the utility tunnel is obtained as follows:

$$R = P_i \times \sum_j \left(C_{ij}\right), \tag{18}$$

where P_i denotes the probability of occurrence of event i, $i = 1, 2, \ldots, n$, and C_{ij} denotes the loss caused by event i (which includes building loss and cable and equipment losses, $j = 1, 2$).

(1) Building Loss. As is known to all, fire will do damage to concrete structures. A series of chemical and physical changes will occur inside the concrete as the temperature rises, which affects the mechanical properties of the concrete and finally results in the instability of the utility tunnel [38, 39]. A large number of scholars found [40–42] that when the surface temperature of concrete is lower than 500°C, the loss of concrete strength is rare. When the surface temperature of concrete is [500°C, 600°C], the bonding force between concrete and steel bar begins to decrease, and the strength loss of concrete is less than 30%. When the surface temperature of concrete rises to [600°C, 700°C], the bonding force reduces greatly and the strength of concrete losses about 50%. When the surface temperature of concrete is up to [700°C, 750°C], the bonding force between concrete and steel bar is severely damaged and the strength loss of concrete is more than 50%. When the surface temperature of concrete is higher than 750°C, concrete spalling occurs in a large area and the bonding force between the steel bar and concrete is seriously damaged, with the concrete strength loss reaching more than 60%. This is based on the distribution of temperature in the utility tunnel when the fire occurs. Table 1 gives the quantitative relationship of building losses.

(2) Cable and Equipment Losses. The temperature of the utility tunnel reaches the cable ignition temperature (330°C), and the cable is considered as ignited. Simultaneously, the cable and equipment are completely damaged. In order to ensure that the cable and equipment losses are consistent with the building loss, the cable and equipment losses ranks are also correspondingly divided into five ranks. Table 2 gives the quantitative relationship of cable and equipment losses. L denotes the distribution range of the temperature in the utility tunnel exceeding 330°C.

Based on the tunnel loss given by Hao and Huang [43], and in accordance with the definition of building loss and cable and equipment loss in this paper, the final loss rank is divided into five ranks, as shown in Table 3.

3.4.2. Risk Matrix. In order to comprehensively evaluate and analyze the risk accidents of the project to guide a risk decision, it is necessary to grade the risk levels of different

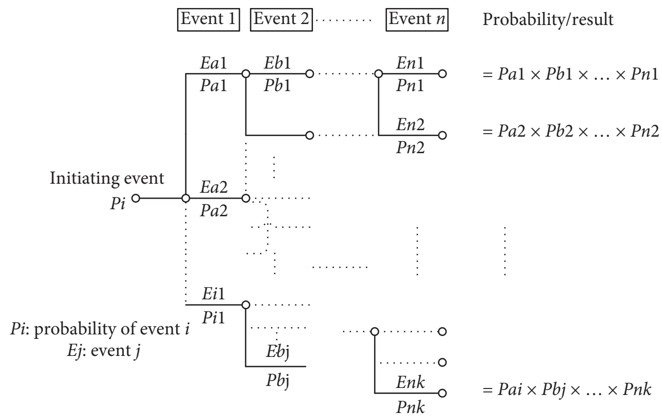

Figure 3: Event tree reasoning process.

Table 1: Building loss.

Temperature (°C)	Building damage rank
[20, 500]	1
[500, 600]	2
[600, 700]	3
[700, 750]	4
[>750]	5

Table 2: Cable and equipment losses.

L (m)	Cable and equipment losses rank
$(0.0L, 0.2L]$	1
$(0.2L, 0.4L]$	2
$(0.4L, 0.6L]$	3
$(0.6L, 0.8L]$	4
$(0.8L, 1.0L]$	5

Table 3: Loss rank.

$\sum_j (C_{ij})$	Loss rank
0~2	①
2~4	②
4~6	③
6~8	④
8~10	⑤

risk accidents. Based on the risk matrix given by Hao and Huang [43] and combined with the engineering practice, the standard for the probability of risk accidents is given in Table 4. Moreover, Table 5 shows the risk level gradation of a utility tunnel cable fire.

4. Case Study

Guizhou Liupanshui City is one of the top ten pilot cities for the utility tunnel as identified by the state in 2015. The project is located in the downtown area of Liupanshui with a total of 14 underground utility tunnels totaling 39.69 km and an estimated total investment of 2.994 billion yuan. The utility tunnel (K5 + 530~K2 + 500) project is in the northern section of Yude Road, Liupanshui City, with a total length of 3.3 km. The utility tunnel exhibits a branch-like arrangement and intersects with the eastern section of the Tianhu Lake and western section of the Tianhu Lake with a single layer layout and partial undercut. The Yude Road utility tunnel is a single-storey box structure in which the cable cabin exhibits a width of 2 m and a height of 2.7 m. The example is used to analyze a combination of weighted fuzzy Petri nets and event trees to quantitatively evaluate the feasibility of utility tunnel cable fires.

Table 4: Probability rank standard.

Probability	Probability rank
$(0, 10^{-4}]$	A
$(10^{-4}, 10^{-3}]$	B
$(10^{-3}, 10^{-2}]$	C
$(10^{-2}, 10^{-1}]$	D
$(10^{-1}, 1]$	E

Table 5: Risk assessment matrix.

Risk			Accident loss				
			①	②	③	④	⑤
Probability	A	$(0, 10^{-4}]$	①A	②A	③A	④A	⑤A
	B	$(10^{-4}, 10^{-3}]$	①B	②B	③B	④B	⑤B
	C	$(10^{-3}, 10^{-2}]$	①C	②C	③C	④C	⑤C
	D	$(10^{-2}, 10^{-1}]$	①D	②D	③D	④D	⑤D
	E	$(10^{-1}, 1]$	①E	②E	③E	④E	⑤E

Note: green denotes that the risk level corresponds to level I, blue denotes that the risk level corresponds to level II, light yellow denotes that the risk level corresponds to level III, dark yellow denotes that the risk level corresponds to level IV, and red denotes that the risk level corresponds to level V.

4.1. Prefire Analysis Based on WFPN

4.1.1. Hazard Identification of Utility Tunnel. The utility tunnel cable cabin is mainly suitable for underground power transmission and distribution in urban areas, and it is difficult for nonworkers to enter. Figure 4 shows the Petri nets used to identify the risk factors that may cause cable fires [9, 10]. Cable

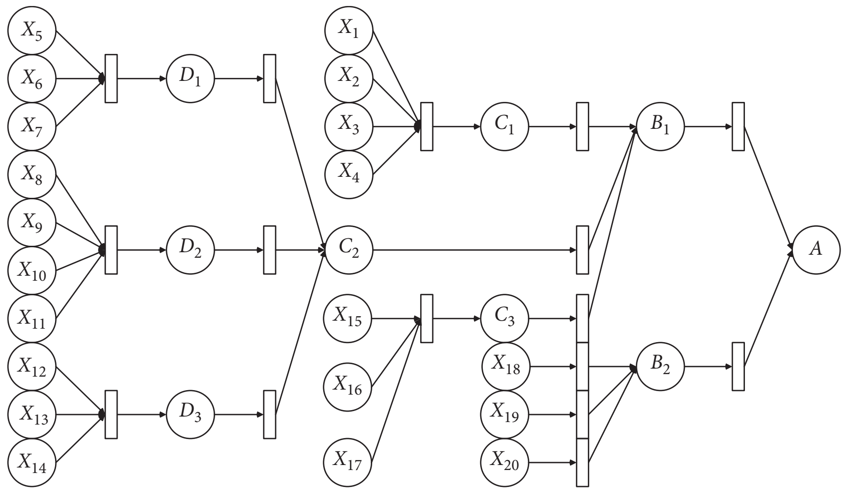

Figure 4: Utility tunnel cable fire weighted fuzzy Petri net.

Table 6: Description of all the events.

No.	Description
X_1	Insufficient thickness of insulation
X_2	Cable creep
X_3	Dielectric strength reduction
X_4	Insulation compression
X_5	Joint corrosion
X_6	Damaged insulation
X_7	Poor installation quality
X_8	Overvoltage
X_9	Overload
X_{10}	Stray currents
X_{11}	Breaker failure
X_{12}	Unreasonable cable arrangement
X_{13}	Cable cabin design is not reasonable
X_{14}	Fan failure
X_{15}	Insulation carbonization
X_{16}	Air arc failure
X_{17}	Insulation layer pyrolysis
X_{18}	Transformer failure
X_{19}	Current transformer failure
X_{20}	Voltage transformer failure
B_1	Cable fires
B_2	Electrical equipment fires
C_1	Dielectric breakdown of insulator
C_2	Cable core overheating
C_3	Arc failure
D_1	Poor connections
D_2	Cable overload
D_3	Poor heat dissipation
A	Cable cabin fires

cabin fires were used as top events for weighted fuzzy Petri nets. Cause of top-level events include cable fires and electrical equipment fires among others. Weighted fuzzy Petri nets of the utility tunnel cabin are mainly composed of the following primary events. Table 6 describes the primary events, intermediate events, and top events in detail [11, 12, 44, 45].

4.1.2. Failure Probability of Primary Event. The multiexpert scoring method and AHP method were used to reduce the impact of different experts on the assessment of each event. The expert competency assessment index system is shown in Figure 5. Table 7 provides a brief introduction of each expert used in the study.

An AHP analysis is used to define expert weights as follows:

$$w_{ej} = (0.3427, 0.2400, 0.2642, 0.1531). \tag{19}$$

We use equation (4) to integrate different opinions of experts into a comprehensive opinion. The primary event X_6 is discussed as an example. The linguistic expressions given by the four experts are as follows: low, low, medium, and very low. The integrated fuzzy number is thus described as follows:

$$\begin{aligned} f(x) &= \max\left(\left(w_{e1} + w_{e2}\right) \cdot f_{\mathrm{L}}(x) \Lambda w_{e3} \cdot f_{\mathrm{M}}(x) \Lambda w_{e4} \cdot f_{\mathrm{VL}}(x)\right) \\ &= [(0.140\lambda + 0.138), 0.449 - 0.156\lambda]. \end{aligned} \tag{20}$$

The corresponding membership function of the above fuzzy number $f(x)$ is defined as follows:

$$f(x) = \begin{cases} \dfrac{x - 0.138}{0.140}, & 0.138 < x \leq 0.278, \\ 1, & 0.278 < x \leq 0.293, \\ \dfrac{0.449 - x}{0.156}, & 0.293 < x \leq 0.449, \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

Figure 6 shows the fuzzy number and its associated membership function.

Subsequently, $\sup[f_{\mathrm{M}}(x) \Lambda f_{\max}(x)] = 0.3883$ and $\sup[f_{\mathrm{M}}(x) \Lambda f_{\min}(x)] = 0.7564$ were calculated by using equations (7) and (8).

The fuzzy possibility score of the fuzzy number is calculated based on equation (6) as follows:

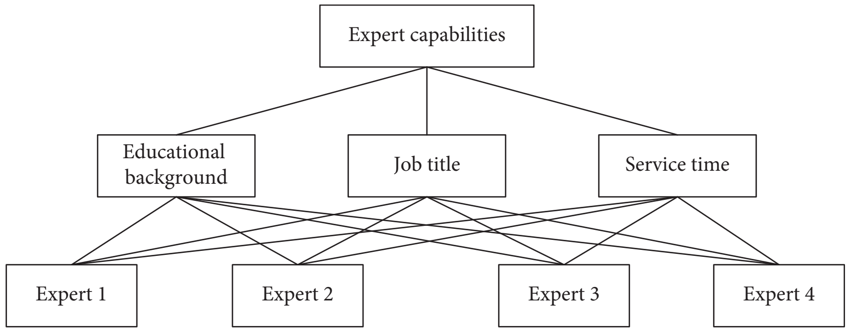

Figure 5: Index system of the AHP for expert capability.

Table 7: Introduction of experts consulted in the case study.

No.	Educational background	Job title	Service time
Expert 1	Bachelor	Professor	30
Expert 2	Junior college	Associate professor	20
Expert 3	Doctor	Professor	13
Expert 4	Doctor	Associate professor	8

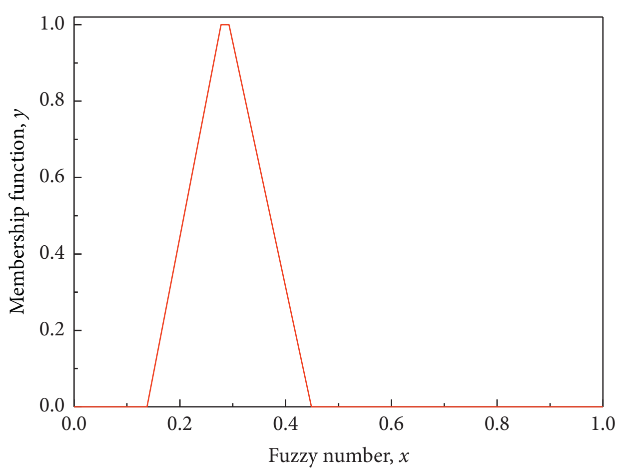

Figure 6: Membership function of X_6.

$$F_M = 0.3159. \quad (22)$$

Finally, X_6 fuzzy failure probability is calculated based on equations (9) and (10) as follows:

$$F = 1.055 \times 10^{-3}. \quad (23)$$

The linguistic expressions of other primary events from the experts are listed in Table 8. Their probabilities are also calculated and are also shown in Table 8. Simultaneously, the statistical probability of partial cable equipment failure is given.

Table 8: Expert language expressions and probabilities of primary events [46].

Primary event	Linguistic expressions				Probability
X_1	VL	L	L	VL	$1.938E-04$
X_2	VL	VL	L	L	$1.402E-04$
X_3	L	VL	L	VL	$2.713E-04$
X_4	VL	L	VL	VL	$6.184E-05$
X_5	VL	VL	L	L	$1.402E-04$
X_6	L	L	M	VL	$1.055E-03$
X_7	L	VL	M	L	$8.962E-04$
X_8	L	VL	VL	L	$1.881E-04$
X_9	VL	L	L	VL	$1.938E-04$
X_{10}	VL	L	L	L	$3.153E-04$
X_{11}		—			$9.600E-04$
X_{12}	H	H	VH	H	$2.752E-02$
X_{13}	M	H	H	M	$9.774E-03$
X_{14}	L	L	M	VL	$1.056E-03$
X_{15}	L	VL	VL	VL	$1.267E-04$
X_{16}	VL	L	VL	L	$1.083E-04$
X_{17}	VL	L	VL	M	$2.104E-04$
X_{18}		—			$3.270E-03$
X_{19}		—			$8.000E-04$
X_{20}		—			$6.100E-04$

4.1.3. Top Event Reasoning and Analysis. The weights of each position in the weighted fuzzy Petri net are given based on AHP, as shown in Table 9.

For the weighted fuzzy Petri net, we obtain the following:

$$W = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ 0 & 0 & \ddots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & & 0 \end{pmatrix}_{29\times 16},$$

$$U = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ 0 & 0 & \ddots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 \\ 0 & 0 & & 1 \end{pmatrix}_{29\times 16},$$

Table 9: Weight of the weighted fuzzy Petri net.

	C_1				C_3				
w_{X_1}	w_{X_2}	w_{X_3}	w_{X_4}	$w_{X_{15}}$	$w_{X_{16}}$	$w_{X_{17}}$			
0.3637	0.0909	0.3637	0.0909	0.3637	0.0909	0.3637			
	D_1				D_2				D_3
w_{X_5}	w_{X_6}	w_{X_7}	w_{X_8}	w_{X_9}	$w_{X_{10}}$	$w_{X_{11}}$	$w_{X_{12}}$	$w_{X_{13}}$	$w_{X_{14}}$
0.4000	0.4000	0.4000	0.4000	0.4000	0.4000	0.4000	0.2500	0.2500	0.5000

$$M_0 = \begin{pmatrix} 0.00019 \\ 0.00014 \\ \vdots \\ 0.00061 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad M_3 = \begin{pmatrix} 0.00019 \\ 0.00014 \\ \vdots \\ 0.00061 \\ 0.00066 \\ 0.00049 \\ 0.01007 \\ 0.00019 \\ 0.01007 \\ 0.00017 \\ 0.01007 \\ 0.00327 \\ 0.00327 \end{pmatrix},$$

$$M_1 = \begin{pmatrix} 0.00019 \\ 0.00014 \\ \vdots \\ 0.00061 \\ 0.00066 \\ 0.00049 \\ 0.01007 \\ 0.00019 \\ 0 \\ 0.00017 \\ 0 \\ 0.00327 \\ 0 \end{pmatrix}, \quad M_4 = \begin{pmatrix} 0.00019 \\ 0.00014 \\ \vdots \\ 0.00061 \\ 0.00066 \\ 0.00049 \\ 0.01007 \\ 0.00019 \\ 0.01007 \\ 0.00017 \\ 0.01007 \\ 0.00327 \\ 0.01007 \end{pmatrix},$$

$$M_2 = \begin{pmatrix} 0.00019 \\ 0.00014 \\ \vdots \\ 0.00061 \\ 0.00066 \\ 0.00049 \\ 0.01007 \\ 0.00019 \\ 0.01007 \\ 0.00017 \\ 0.00019 \\ 0.00327 \\ 0.00327 \end{pmatrix}, \quad M_5 = \begin{pmatrix} 0.00019 \\ 0.00014 \\ \vdots \\ 0.00061 \\ 0.00066 \\ 0.00049 \\ 0.01007 \\ 0.00019 \\ 0.01007 \\ 0.00017 \\ 0.01007 \\ 0.00327 \\ 0.01007 \end{pmatrix}. \tag{24}$$

When k equals 5, M_4 equals M_5. This implies that a transition in the WFPN system cannot be executed, and the system reached a stable state. In M_5, the marking of place P_A corresponded to 0.01007, which denotes the final probability value of a fire.

4.1.4. Sensitivity Analysis. It is important for risk management to analyze the impact of different risk factors on risk assessment results and obtain key risk factors [47, 48]. Sensitivity analysis is particularly useful in investigating the performance of each input factor's contribution to the occurrence of an output event. Due to complexity and particularity of the utility tunnel environments, great fuzziness exists during the determination of evaluation each factor. Considering that the parameters may fluctuate around a mean value due to uncertainties and errors, it is therefore useful to perform a sensitivity analysis [49]. In the study, the observed value of each evaluation factor P_i is assumed to suffer from a fluctuation of −30%, −20%, −10%, +10%, +20%, and +30% of its initial value. As shown in equation (25), the degree of influence of the change in P_i on the top event A as shown in Figure 7 is as follows:

$$\Delta P_A = \frac{P'_A - P_A}{P_A}, \tag{25}$$

where P_A denotes the probability of top event under initial conditions, P'_A denotes the probability of top event considering the fluctuation of each evaluation factor P_i, and ΔP_A denotes the rate of change in the top event probability.

As shown in Figure 7, when the evaluation index changes, unreasonable cable arrangement (X_{12}) and cable cabin design are not reasonable (X_{13}) and fan failure (X_{14}) have an impact on the top event P_A, which the rate of change in the top event probability corresponds to $X_{12} > X_{13} > X_{14}$, but when the probability of other primary events changes, there is little impact on the probability of top events. This finding suggests that the three factors have the most important effect on safety construction of the utility tunnel.

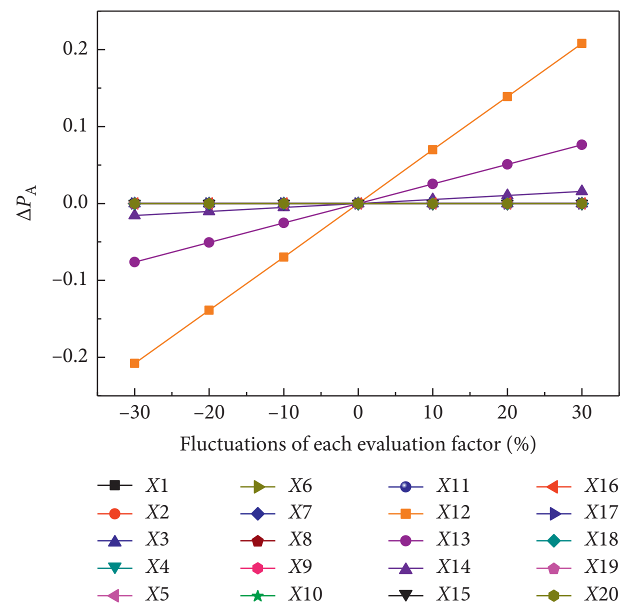

Figure 7: Effect of risk factor fluctuations on top event probability.

$$\begin{aligned} P_1 &= P_A \cdot P_{s1} \cdot P_{s2} \cdot P_{s3} = 0.00826; \\ P_2 &= P_A \cdot P_{s1} \cdot P_{s2} \cdot (1 - P_{s3}) = 0.00034; \\ P_3 &= P_A \cdot P_{s1} \cdot (1 - P_{s2}) \cdot P_{s3} = 0.00082; \\ P_4 &= P_A \cdot P_{s1} \cdot (1 - P_{s2}) \cdot (1 - P_{s3}) \cdot P_{s4} = 0.00003; \\ P_5 &= P_A \cdot (1 - P_{s1}) = 0.00061. \end{aligned} \tag{26}$$

4.2. Postfire Analysis Based on ETA-FDS

4.2.1. Consequence Scenario Analysis. The ETA is used to analyze the cable fire consequences of the utility tunnel, as shown in Figure 8. There are four control measures in the fire analysis model: monitoring and alarm systems, fire doors, automatic fire suppression systems, and fire brigades. The early warning and alarm systems continuously monitor temperature changes inside the pipe gallery and send out alarm messages. When a fire is successfully detected, the fire door and the automatic fire extinguishing system are controlled by computer linkage to control the fire. When the linkage control measures fail, it is necessary to dispatch the fire brigade in time to extinguish the fire.

Table 10 gives the various barrier symbols and their probabilities. The probability of a consequence is obtained based on the inference rules of the event tree.

4.2.2. Quantitative Analysis of Consequences. When cable fires occur in a utility tunnel, there are differences in the losses caused by different fire identification methods and fire extinguishing methods from the discovery of fire to the suppression of fire. In the study, the FDS numerical model is established to obtain the temperature distribution under various conditions, and the temperature is then used to quantify the fire loss.

The full-size model is based on the utility tunnel cabin of Liupanshui, Guizhou. The main model of the tunnel (2.0 m wide, 2.7 m high, and 200 m long) is established, which is divided into 9,600 $0.50 \times 0.45 \times 0.50$ meshes. Furthermore, $1.0\,\text{m} \times 1.7\,\text{m}$ fire doors are arranged at both ends of the fire protection zone, and $0.9\,\text{m} \times 1.0\,\text{m}$ natural air inlets and mechanical air outlets are arranged at the top of the utility tunnel, with wind speeds corresponding to 1.2 and 3 m/s, respectively.

The 0.5 m-wide brackets are arranged at both ends of the utility tunnel, and 110 kV and 10 kV copper core flame-retardant cable (ZRYJV) and copper core flame-retardant wire (ZRBV) are laid. The cable material is simplified to a flat plate that only consists only of a flame-retardant material external to the cable [7]. In the model, the top of the tunnel is arranged with temperature sensing detectors starting from $z = 5$ m and installed at intervals of 15 m, thereby setting the section at $x = 1.0$ m for temperature observation and placing a fire extinguishing nozzle at every 2.5 m, and the position of the first nozzle (1, 2.5, and 2.6 m) is as shown in Figure 9.

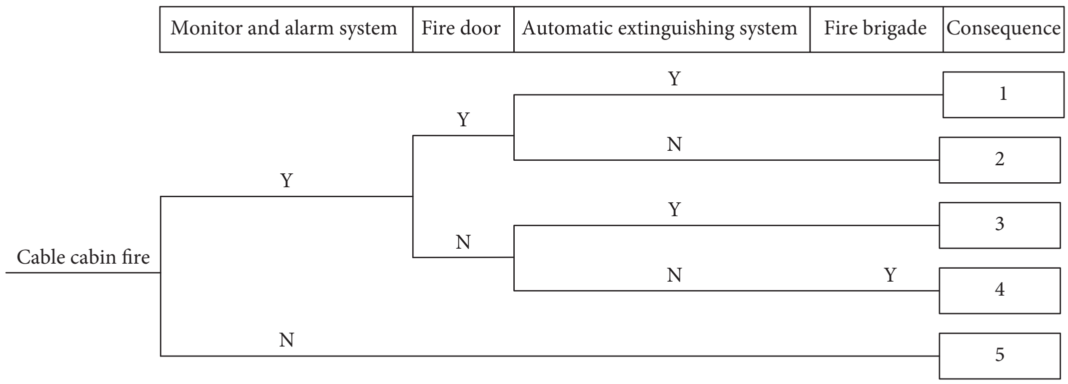

Figure 8: Utility tunnel cable fire event tree model.

Table 10: Safety barrier and its probability [50].

Symbol	Safety barrier	Probability
S_1	Monitor and alarm barrier	0.939
S_2	Fire door barrier	0.910
S_3	Automatic fire extinguishing system barrier	0.960
S_4	Fire brigade barrier	1.000

Notes: given the limit of the fire site, the fire is controlled within a certain range by blocking if the cable fire of the utility tunnel is determined in time, and thus, the fire is successfully extinguished by default when a fire brigade arrives.

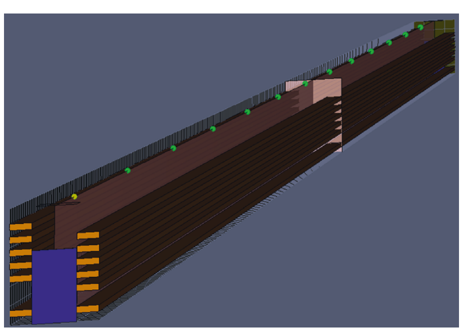

Figure 9: Model of the utility tunnel.

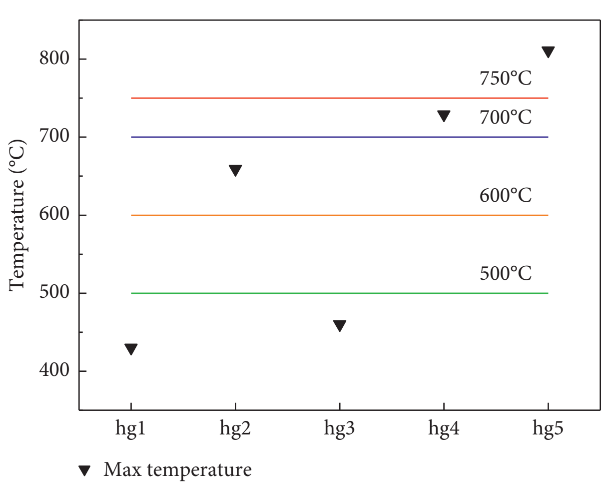

Figure 10: Maximum temperature of the utility tunnel under different consequences.

The utility tunnel cable cabin early warning and alarm systems work continuously and issue timely alarm information to control active and passive fire prevention facilities and fire brigade response.

With respect to consequence 1, when the temperature exceeds the alarm threshold, the fire door is closed, and the fire suppression system is activated. With respect to consequence 2, the fire door is closed when the temperature exceeds the alarm threshold. With respect to consequence 3, the fire suppression system is activated when the temperature exceeds the alarm threshold. With respect to consequence 4, in t_{01}, the warning and alarm system detect the occurrence of the fire but neither the fire door nor the fire suppression system are activated. Hence, it is necessary to dispatch the fire brigade to extinguish the fire. The response time of the fire brigade corresponds to t_4 ($t_4 = 5$ min [51]). The utility tunnel is a limited space when the fire brigade begins to extinguish the fire, and thus the fire no longer expands to both ends. Among them, with respect to the detection time of the early warning and alarm system: when the temperature parameter is used as the detection value, the temperature detection threshold corresponds to 68°C [13]. With respect to consequence 5, the fire corresponds to uncontrolled burning because no fire is detected.

(1) Building Loss. Fire-fighting measures are initiated when the temperature exceeds the alarm threshold. Figure 10 shows the maximum temperature distribution in the utility tunnel under various consequences.

(2) Cable and Equipment Losses. Fire-fighting measures are initiated when the temperature exceeds the alarm threshold. Under each consequence, the maximum temperature distribution of each measuring point in the utility tunnel is shown in Figure 11.

When the fire door is normally closed and the fire extinguishing system is in effect: Figure 10 shows the maximum temperature of the utility tunnel is lowered from 811°C to 430°C. As shown in Figure 11 (hg5 and hg1), the distribution range of cable ignition temperature (>330°C) decreases from almost the entire utility tunnel to only near T_2, T_3, T_4, T_7, and T_{11}.

When the fire door is normally closed, Figure 10 shows the maximum temperature of the utility tunnel is reduced

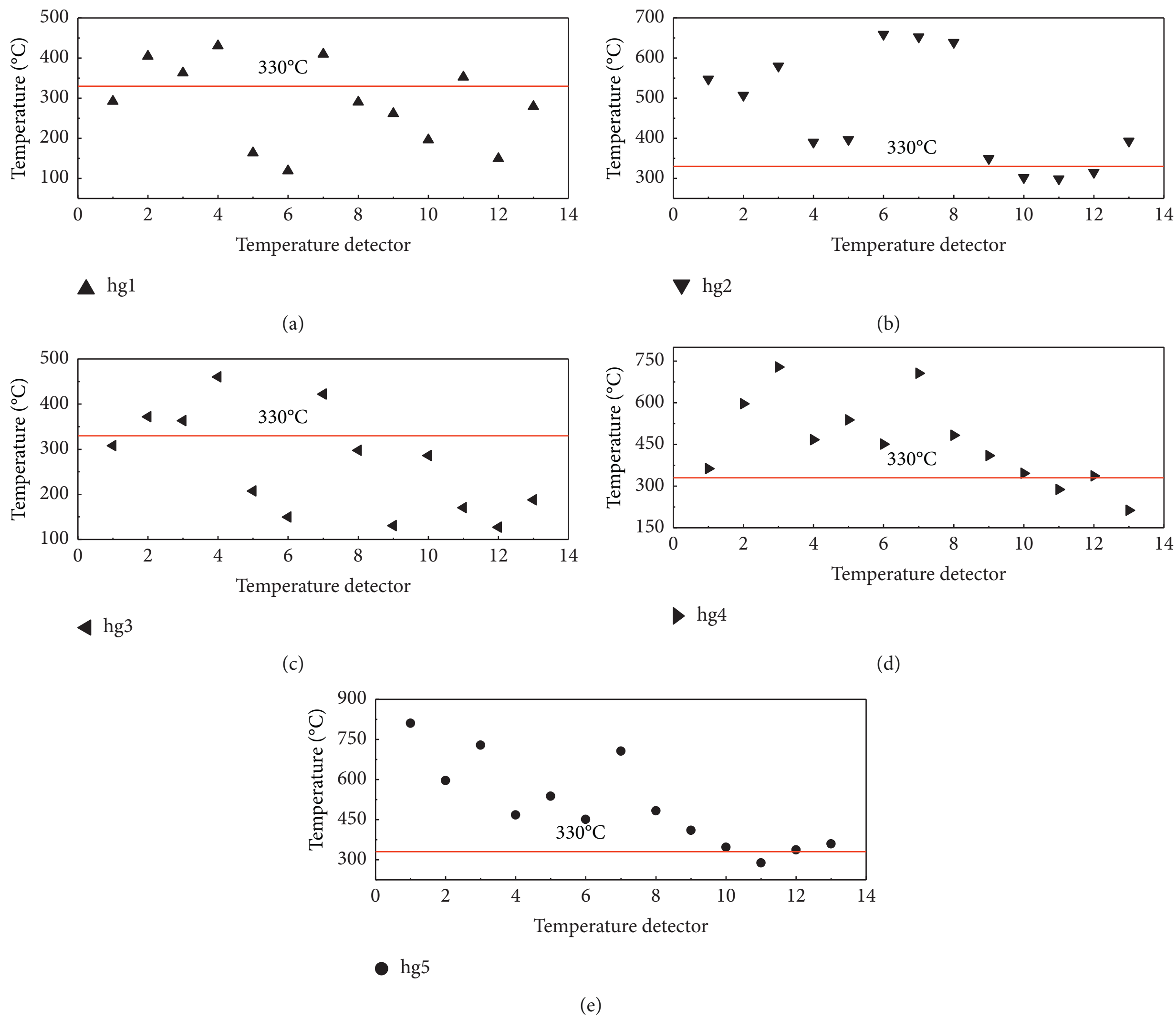

Figure 11: Highest temperature of each measuring point of the utility tunnel.

Table 11: Quantification of each consequence of fire risk.

Consequence	Probability	Probability level	Losses			Risk rank	
			Building loss	Cable and equipment loss	Loss level		
1	0.00826	C	1	2	②	②C	II
2	0.00034	B	3	4	④	④B	III
3	0.00082	B	1	2	②	②B	II
4	0.00003	A	4	4	④	④A	III
5	0.00061	B	5	5	⑤	⑤B	IV

from 811 to 659°C. As shown in Figure 11 (hg5 and hg2), the temperature of other detectors exceeds 330°C with the except of T_{10}, T_{11}, and T_{12}.

When the fire extinguishing system is in effect, Figure 10 shows the maximum temperature of the utility tunnel decreases from 811 to 460°C. As shown in Figure 11 (hg5 and hg3), the distribution range of cable ignition temperature (>330°C) decreases from almost the entire utility tunnel to only near T_2, T_3, T_4, and T_7.

When the fire brigade successfully extinguished the fire, Figure 10 shows the maximum temperature of the utility tunnel decreases from 811 to 729°C. As shown in Figure 11 (hg5 and hg4), the cable near T_{11} and T_{13} does not reach the ignition temperature.

In summary, the fire door exhibits an extremely limited extinguishing effect on fires, and the fire extinguishing system plays a key role in the fire extinguishing. Simultaneously, given the fire in the limited space of the utility tunnel, it is difficult for firefighters to enter the fire front to fire-extinguish. Therefore, the fire brigade's ability to extinguish the fire is also extremely limited. However, fire doors and fire brigades are extremely effective in controlling the spread of fires to adjacent fire zones and controlling fires within a fire zone. In addition, when the early warning and alarm system successfully identifies the occurrence of fire, we activate various fire-fighting facilities, and this is the decisive factor that determines whether we can control the fire within a fire zone.

In combination with Tables 1–5, the quantified values of fire loss and risk for each consequence are given in Table 11.

As shown in the above table, the risk rankings of each consequence are $R_5 > R_2 = R_4 > R_1 = R_3$. The utility tunnel is at the highest risk value of the consequence 5, and thus, it is necessary to focus on the control measures related to the consequence 5. On the one hand, we reduce the probability of accidents. Thus, it is necessary to focus on the cable arrangement, cable compartment design, and fan status. On the other hand, to reduce the severity of the consequences, it is necessary to focus on the early warning and alarm system to ensure that it successfully detects a fire.

5. Conclusion

This paper proposes a method of quantitatively assessing the fire risk of utility tunnel cables. The innovation of the method is combined with weighted fuzzy Petri nets, event trees, and FDS simulation. A systematic procedure is proposed to analyze and evaluate the likelihood of occurrence of the initiating events, scenarios, and consequences. Specifically, WFPN, ETA, and FDS methods are used to calculate the probability and consequence of utility tunnel cable fire events in various scenarios. A detailed study was conducted on a cable cabin of the Liupanshui utility tunnel in Guizhou. Case studies indicated that the method aided in hazard identification, risk consequence assessment, and security management. Through using the proposed method, key factors for disasters, key measures for fire control, and key measures for fire suppression can be obtained to provide reliable guidance for safety management.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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