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Research on Intelligent Monitoring of Fire Safety and Fire Rescue Plan for Tunnel Operation under Quasi-Unattended Background

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Abstract: Tunnel structures account for la large proportion of the structures in mountain highway transportation systems. Most tunnels are located in remote areas in which the geological conditions are complex and harsh and in which the layout of the management facilities along the way is complex. Thus, the management and maintenance costs of various facilities are expensive, the cost of fire safety operations and management is high, and disaster prevention and rescue have a difficult time meeting the objective requirements. Therefore, it is urgent to carry out research on quasi-unmanned operations and intelligent remote monitoring. This study firstly proposes a fire safety intelligent monitoring framework for quasi-unattended tunnels. By making full use of various intelligent sensor monitoring data in the tunnel, the tunnel operation status can be grasped in real time. Then, a fire safety evaluation model can be established through the analytic hierarchy process (AHP), and, based on the monitoring data, the AHP model parameters can be evaluated to realize the real-time evaluation and management of tunnel fire safety. Finally, on the basis of the fire safety intelligent monitoring system and the fire safety evaluation system, an adaptive fire rescue plan formulation scheme is proposed for the quasi-unattended tunnels so as to provide guaranteed support for the rapid automatic response of tunnel fire protection and to provide technical data support for the design and realization of intelligent and efficient tunnel management

Keywords: tunnels; fire safety; intelligent monitoring; fire rescue plan; emergency management

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1. Introduction

The highway transportation systems in mountain areas are characterized by a large proportion of tunnels, and, generally, these tunnels are located in remote areas with harsh geological conditions and complex layouts for the management facilities, which have high operational safety risks. Thus, there exist higher requirements for disaster prevention and rescue and higher requirements for the response speed of tunnel fire emergencies. Under the background of the current tunnel quasi-unattended management system, there are fewer tunnel site management personnel, and, thus, it is highly urgent to carry out research on the intelligent monitoring of fire safety and fire rescue plans for tunnel operations, which can help to strengthen the intelligent management and maintenance level of the fire control and various monitoring facilities in tunnels. The shortcomings of the existing management system, e.g., being time-consuming, being laborious, and having a high cost, can be overcome, and the speed of the fire emergency response can also be improved because of the enhancement of intelligent monitoring and the management level.

Many scholars have put forward some exploratory research related to the field of tunnel quasi-unattended management and the intelligent monitoring of fire safety. In terms of unattended tunnel research, Gao et al. [1] proposed the prototype of the construction idea for an unattended tunnel management station as early as 2009. Yang [2] has carried out relevant research on the intelligent maintenance of tunnel electromechanics. Based on the monitoring host, remote power management controller, terminal data acquisition equipment (the temperature and humidity sensor, smoke detector, water intrusion detector, access control, infrared sensor, etc.), monitoring management software system, and other software and hardware, a set of unattended monitoring schemes for tunnel substations have been formed, and it has been successfully applied in the scenarios of highway tunnel substations and has achieved good application results [3]. By analyzing the problems existing in the equipment room during maintenance work, Peng [4] proposed a set of unattended intelligent monitoring systems. Through the construction of this system, the intelligent management of an equipment room can be realized, the cost of mechanical and electrical maintenance can be reduced, and the stable operation of each operation system of an expressway can be ensured. Chen [5] designed an intelligent unattended monitoring and management system using Internet of Things technology, which can monitor the operation status of highway tunnels in real time; additionally, once it encounters an abnormal situation, it can immediately send an alarm to the administrators, and the safety of tunnels can be guaranteed. Qin [6] described a method to implement the fire prevention and control function of micro fire stations. A micro fire station is generally set up at the tunnel portal. In order to save rescue time, the micro fire station mainly stores some portable fire-fighting equipment near the tunnel portal that may be needed at the fire scene when necessary, e.g., fire extinguishers, fire hydrant wrenches, fire blankets, fire axes, jacks, standby fixed telephones, etc. Once the fire occurs, the on-site personnel do not have to wait for the arrival of the fire engine and can directly use the portable fire-fighting equipment in the micro fire station to carry out the fire-extinguishing work, which can improve the fire-extinguishing efficiency. Yu et al. [7] studied the actual situation of micro fire stations and elaborated on the problems of the personnel quality, equipment maintenance, the training and assessment system, and the infrastructure system in the fire stations. Based on the investigation and analysis of micro fire stations in existing communities, Cao and Wang [8] analyzed the defects and deficiencies in the use of these fire stations, such as the distribution, structure, function, and equipment in the use phases, and designed a modern community miniature fire station with perfect functions, space, layout, and equipment. Feng and Ji [9] proposed a series of improvement methods that can be implemented, including the rational use of existing resources and relying on modern technology to implement intelligent management. Taking the necessity of promoting the construction of micro fire stations as the starting point, Bian et al. [10] proposed a detection model based on an optical fiber distributed temperature sensing (FO-DTS) system and a depth anomaly for urban public-tunnel fire accidents that can effectively monitor fire releases in the early stage.

Li [11] analyzed the problems in the aspects of construction coverage, the operation and maintenance guarantee mechanism, the relevant supporting system's construction, and emergency linkage in the process of promoting micro fire stations and put forward methods and suggestions for maximizing their effectiveness with respect to six aspects. Du [12] put forward the overall idea of research in the view of the research status and shortcomings of the highway tunnel power supply systems at home and abroad. Wang [13] introduced the power supply design of the Guangzhou New International Airport Expressway, which focused on the new ideas of the power supply design and the new technologies used. Based on the study of more than 30 highway tunnel operation cases, Su et al. [14] conducted research on highway tunnel operation risk modelling and tunnel operation real-time monitoring. Five types of emergency incidents were identified and classified with regard to the effect of the incidents on the tunnel operation risks and efficiency, and, furthermore, a risk evaluation model was established to grade the impact of various emergencies on the tunnel operation safety. Yang et al. [15] conducted an economic analysis of the assembly of "prefabricated cabin" temporary construction facilities with respect to substation engineering and made suggestions on the promotion and application of temporary construction facilities. A prefabricated cabin can be used as a micro fire station. Some fire-fighting equipment can be stored inside prefabricated cabins. Compared with the traditional reinforced concrete civil structures, prefabricated cabins have the advantages of a low cost, fast construction, less area occupation, and better mobility. In terms of tunnel emergency management, Luo [16] contacted many specific cases of road tunnel traffic accidents and fire accidents at home and abroad as well as the analysis results of the hazards of road tunnel accident types. The technical route of the research on the safe operation and management of the Qinling Ultimate Nanshan Highway Tunnel was proposed, and the corresponding management system and management method were formulated, which were applied in the actual operation and management of the Qinling Ultimate Nanshan Highway Tunnel. Nellen et al. [17] reported the application test of a new fiber Bragg grating (FBG) sensor element for long-term tunnel monitoring, which provided basic data support for tunnel monitoring. Wang et al. [18–22] proposed RFID wireless sensing technology for SHM applications as well as different kinds of Bayesian algorithms for SHM data modelling and anomaly detection, which can provide technical support for the management and operation safety of engineering structures. Zeng et al. [23] investigated and counted the highway tunnel fire accidents in China and analyzed the causes and characteristics of the accidents. In addition, research on fire prevention and disaster relief was carried out for long highway tunnels to form an interlinked safety chain to ensure the safety and smooth operation of the highway. Zhan [24], based on the investigation of the traffic safety problems in the section of the long tunnel group that has been operated, takes the technical problems in the field of traffic safety as the core; additionally, according to the operation characteristics and environmental characteristics of the long tunnel group area in the mountainous area, the traffic accident characteristics of the tunnel group area are analyzed, and the traffic flow characteristics are studied. Zhang [25] takes the control of traffic accident emergency plans as the starting point, studies the influencing factors of traffic accidents, and describes the reasonable and feasible traffic accident emergency response institutions and processes. Erd et al. [26] built an event monitoring network in emergency situations through the design and implementation of wireless sensor networks to solve the problem of difficulty in collecting building information, such as tunnels, during disasters. Xuan [27] took the Maanshan Long Highway Tunnel as an example, established a long highway tunnel network and traffic accident model with the help of traffic simulation software, gave safety accident countermeasures through the analysis of the tunnel operation safety factors, and proposed an emergency organization and safety level evaluation method for long tunnels. Zhang [28] analyzed the emergency incidents that occurred in the current long tunnel, quickly dealt with them, disclosed the shortcomings of the business status to the public, proposed the relevant technical framework, and put forward suggestions for subsequent improvements. Qian et al. [29] used big data technology to conduct an in-depth analysis of a very long highway tunnel and combined environmental monitoring data and traffic flow data to construct a data-driven perception model based on the random forest algorithm. Wang et al. [30] started from the types, causes, and characteristics of emergency incidents combined with fire emergency handling work and put forward corresponding emergency plans. Xiao [31] combines the risk management theory and the relevant risk management method guidelines to define the safety risk of highway long tunnel operations. Zhang [32] took the Wuxunxun highway tunnel fire protection project in Yunnan as the research object for tunnel safety evaluation. After comprehensively sorting out and analyzing its safety management status and the influencing factors, Zhang scientifically established an evaluation index system, systematically evaluated its safety management, and then put forward opinions on and suggestions for strengthening safety management.

Generally, there is still a lack of a complete and systematic tunnel quasi-unmanned operation system nationwide. At present, there is local unmanned research on some supporting technologies, such as the automatic monitoring of power supply and distribution systems, tunnel security systems, etc., because the intelligent and quasi-unmanned tunnel operation and management of highway tunnels is the key development direction in the next 20 years or even longer. Therefore, this study closely focuses on the need for quasi-unmanned and intelligent tunnel fire protection (shown in Figure 1) and makes full use of various sensor monitoring data in a tunnel (including video image monitoring, wireless hydraulic pressure monitoring, wireless water flow monitoring, wireless fire hydrant intelligent monitoring, fire equipment power monitoring, wireless independent smoke detection, fire door monitoring, smoke exhaust fan monitoring, emergency lighting and evacuation instruction sign monitoring, etc.) to grasp the tunnel operation status in real time. Then, the "Detection system for fire condition and fire-fighting equipment status" can employ intelligent algorithms to detect and judge the fire situation and the status of the fire-fighting equipment in the tunnel based on the monitoring data. This system can determine whether there is a fire in the tunnel, can determine the size and severity of the fire, and can determine whether there is a fault in the fire-fighting equipment inside the tunnel. If there exists a fault in the fire-fighting equipment, maintenance will be carried out. If a fire accident is detected, the alarm will be triggered to carry out the fire rescue treatment. Then, fire personnel, fire vehicles, fire tools, etc., can be intelligently matched according to the sensor monitoring alarm data type form an adaptive and intelligent fire rescue plan. The tunnel fire safety level can be evaluated through the analytic hierarchy process, and the fire safety status can be classified into five levels (i.e., "A", "B", "C", "D", and "E"). The fire safety level increases from "A" to "E", and, correspondingly, the severity level increases. Finally, according to the fire safety level, the number of firefighters, fire vehicles, fire tools, etc., is intelligently matched to form an adaptive intelligent fire rescue plan. For instance, if the fire accident is serious with a high level, the number of firefighters and fire vehicles matched by the intelligent system will increase, and, conversely, the matched fire force will decrease. Finally, through the research of this project, a set of unmanned sample research results and an application system can be formed so that they can effectively apply and serve the construction of the highway tunnel substation and achieve the purpose of the convenient management, cost saving, 24 h online real-time monitoring, real-time information acquisition, and remote control of the site.

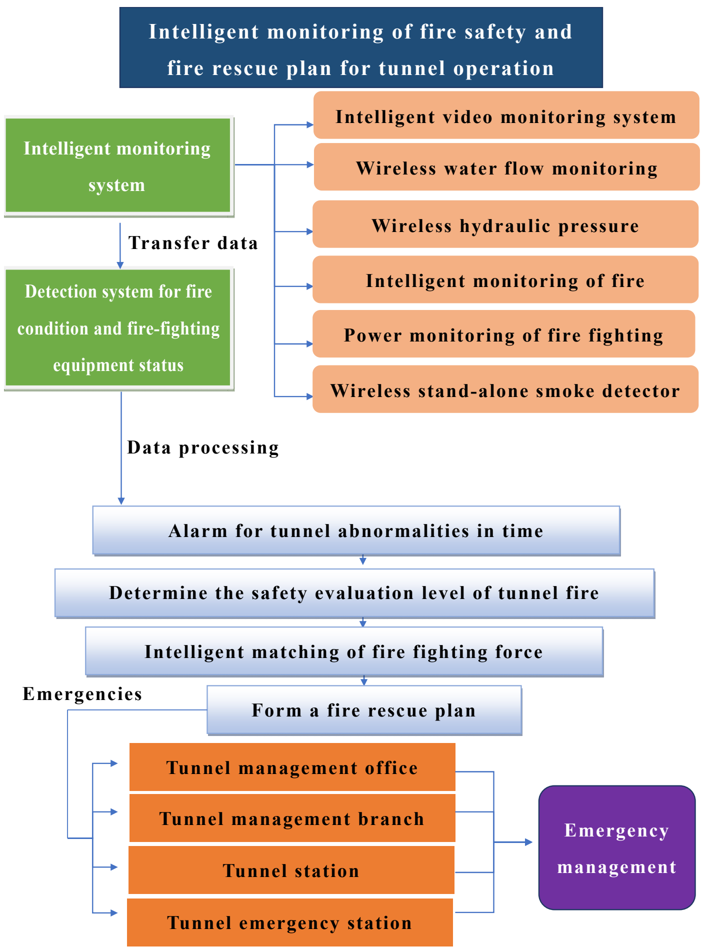

Figure 1. Overall flowchart of tunnel operation safety monitoring.

2. Intelligent Monitoring of Fire Safety for Quasi-Unattended Tunnels

This study proposes an intelligent monitoring system framework of fire safety for quasi-unattended tunnels (shown in Figure 2) that includes video monitoring, wireless hydraulic pressure monitoring, wireless water flow monitoring, wireless fire hydrant intelligent monitoring, fire equipment power monitoring, wireless independent smoke detection, fire door monitoring, smoke exhaust fan monitoring, emergency lighting and evacuation instruction sign monitoring, etc., to grasp the tunnel operation status in real time. A tunnel fire safety monitoring system is the basic equipment in an intelligent fire inspection system that is needed to reliably and effectively collect the status data of fire-fighting facilities. Based on the monitoring alarm data, timely alarms for tunnel abnormalities and the intelligent matching of fire personnel, fire vehicles, fire tools, etc., can be issued, forming an adaptive intelligent fire rescue plan.

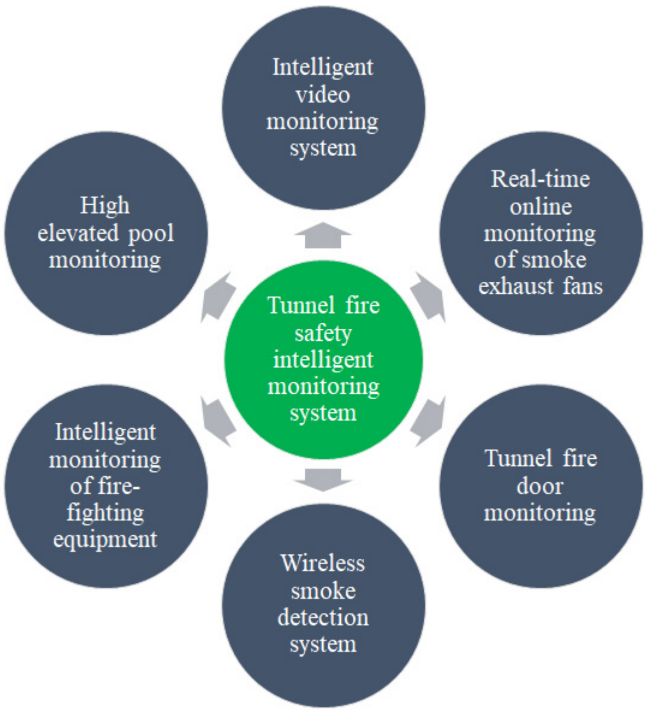

Figure 2. Tunnel fire safety intelligent monitoring system.

2.1. Intelligent Video Monitoring System

In the field of tunnel monitoring, intelligent video monitoring technology has two main functions: the monitoring function and the control function. The monitoring function mainly includes the video monitoring system inside the tunnel, the intelligent video analysis means, and the automated analysis of the monitoring scene through computer vision and video analysis technology to achieve target detection, identification, tracking and statistics, etc. This monitoring module cuts the video data stream, extracts the data frame at equal intervals, and conducts a preliminary data analysis on the corresponding data frame through the sharpening algorithm. Through the video monitoring system, the traffic flow data indicators in the tunnel can be obtained in an all-round way, and the indicators mainly include the model, speed, license plate, and other information of the passing vehicle; the traffic flow data at the tunnel entrance; the vehicle speed and stay time data; the historical data of the traffic flow; etc. Aiming at the semiclosed and complex characteristics of tunnel traffic, prediction analysis techniques can be used to predict the traffic volume and traffic trends in advance and to provide guidance for refined tunnel management and optimal scheduling so as to effectively channel tunnel traffic, to improve tunnel traffic safety, and to reduce the probability of congestion and car accidents. By integrating the intelligent video surveillance function, it can intelligently identify vehicle information, vehicle emergency accidents, wrong-way driving, intrusions into restricted areas, and other behaviors, which helps traffic enforcement departments effectively obtain emergency situations inside the tunnel in time and track suspected vehicles and illegal vehicles. At the same time, fire detection through intelligent image analysis can also be effectively realized so as to quickly respond to fire dangers.

The control function is mainly to realize the intelligent control of the intelligent lighting and signage status of the tunnel. This module is mainly based on the data information provided by the two modules mentioned above and the real-time judgment of whether there is vehicle traffic in the tunnel, and it is then associated with the lighting fixture switch in the tunnel to provide lighting for the road section where vehicles pass, thereby reducing the loss of lighting energy and achieving the intelligent lighting of "the car lights on, the car lights off".

The realization of the monitoring function and control function in the tunnel mainly relies on four modules designed based on video image technology, namely the image acquisition and preprocessing module, vehicle information identification and collection and fire monitoring module, lighting control module, and database module. Based on the real-time and security requirements of tunnel monitoring applications, edge computing devices are used as algorithm carriers, and firewall devices can be appropriately added between switches and cameras. Traffic counting uses a deep learning approach that uses lightweight neural network models to run efficiently on embedded devices. The algorithm detects the target set to the license plate number and assists with image acquisition through an infrared camera so it can adapt to multiangle photography, avoid the shadow influence caused by the high-speed movement of the vehicle, greatly improve the image accuracy, and effectively reduce the recognition error caused by occlusion. The integration of the database module and its combination with big data technology can provide data support for the subsequent construction of the traffic data system, provide a priori conditions for tunnel maintenance, greatly promote the completion of the intelligent transportation system, and improve the modernization level of tunnel monitoring. At the same time, the video image processing technology based on the software design is also convenient for technical updating and can easily add or remove the corresponding functional modules according to the needs of the specific situation, and system maintenance and updating are simple, which overcomes the problem of traditional detection method technology upgrading and equipment replacement.

2.2. Remote and Wireless Monitoring for Highly Elevated Pools

Highway tunnels are often equipped with highly elevated pools to provide the working water pressure required by the fire protection system and to provide the fire protection system with the water needed to extinguish the fire in the early stages of fire extinguishing. Traditionally, the water level monitoring of the highly elevated pool is generally completed through a manual inspection (shown in Figure 3), which is time-consuming, and the installation of wireless sensors in the highly elevated pool can replace manual inspections through remote intelligent monitoring.

Figure 3. Traditional water level monitoring for highly elevated pools.

The remote and wireless monitoring framework is shown in Figure 4, the information collected by the remote and wireless monitoring system includes water level information, water pressure information, and structural damage information (e.g., cracking). This information is transmitted back to the data server through the wireless network, forming the monitoring database as the accumulation layer. Then, these monitoring data are transmitted to the control system after the data analysis, intelligent diagnosis, and fault prewarning. The processed data are sent to the tunnel managers, and the final decisions can be made based on these data.

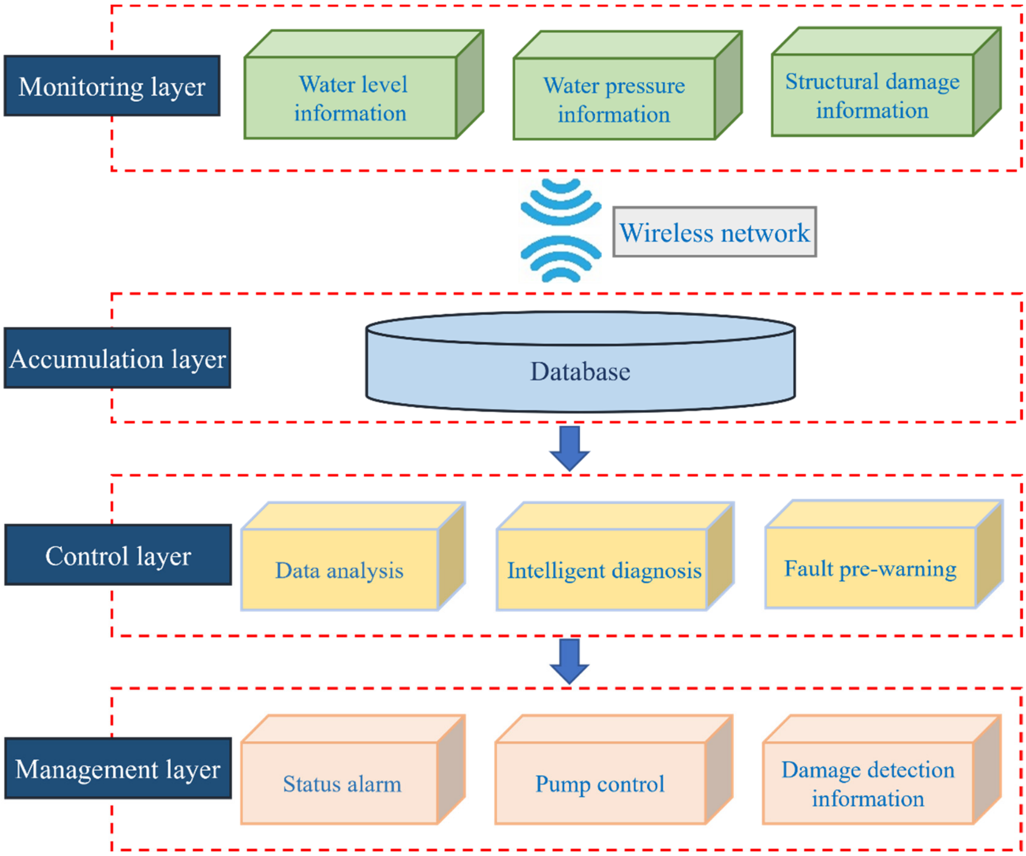

Figure 4. Remote and wireless monitoring framework for highly elevated pools.

When the water level of the highly elevated pool is lower than the set height, the system displays the water shortage status, automatically sends an alarm to the tunnel management department, and also sends the command to turn on the pump. When the water level reaches the specified height, the system will immediately send a command to turn off the pump. At the same time, the system supports setting a standard water pressure and monitors whether the highly elevated pool is above the set standard water pressure in real time with a pressure sensor to ensure that the pool water pressure meets the water pressure of fire-fighting work. When the internal water pressure of the high pool is insufficient, the system automatically turns on the water pump, and, if the specified water level is exceeded but the water pressure conditions are still not met, the system combines the structural damage detection module to determine whether there are cracks or other structural damage in the pool and sends a fault warning to the management department. The remote and wireless monitoring system of a highly elevated pool is a real-time, efficient, and convenient operation that can replace traditional manual inspections and directly reduce the consumption of manpower and material resources. In addition, the remote monitoring system of the high-level pool can ensure that the water volume of the highly elevated pool is sufficient in real time around the clock, and it can effectively ensure sufficient water for the tunnel fire protection system, which can provide more reliable technical support for tunnel fire safety.

2.3. Intelligent Monitoring of Fire-Fighting Equipment

Regarding the monitoring of fire-fighting equipment in tunnels, it is critical to carry out the intelligent monitoring of fire hydrants. Through the design of wireless monitoring equipment, the objective is to monitor whether there is a water leakage in the pipe network of the fire hydrant system, whether the water pressure at the outlet should be met, and whether the fire pump can be started normally. If a fault occurs, an alarm is issued to achieve the purpose of unmanned monitoring.

The fire equipment power supply monitoring system is also crucial and can monitor the power supply status of the fire equipment in real time to ensure that the equipment has a stable energy supply at all times under the working voltage. Its system should include monitoring hosts, sensors, communication lines, etc. The voltage and current sensors collect the voltage and current information of the fire power supply and upload it to the monitoring host. The monitoring host analyzes the voltage and current information collected by the sensors and can diagnose faults such as sudden changes in the voltage and current, short circuits, and leakages. When a fault occurs, the fault type and alarm can be shown to the tunnel management department. Based on this information, the site management and maintenance department can repair it in time according to the fault display to avoid the situation that the fire equipment cannot operate normally due to a power failure when a fire accident occurs. In order to meet the requirements of tunnel operation safety, the monitoring system of the fire-fighting equipment can accurately identify the fault location, fault category, and other information and can issue alarms in time to propose the best solution. The system adopts a common protocol and a standardized external interface, which greatly expands the system hardware and ensures the compatibility of the system, making it suitable for matching various types of integrated monitoring systems. At the same time, the system can be equipped with a fault self-test isolation function, which can regularly self-test, report the fault reason, and interrupt and adjust the monitoring system in time, which effectively reduces the failure rate.

2.4. Wireless Smoke Detection System

The wireless smoke fire detection alarms can be developed based on many Internet of Things technologies, e.g., ZigBee, RFID, 5G, etc. This system is conducive to improving the early warning level for tunnel fire accidents. Through wireless transmission technology, the smoke sensor monitoring data are connected to the tunnel fire safety intelligent monitoring system. The sensor has an automatic alarm function. When the alarm threshold is reached, the alarm function is triggered automatically. After the monitoring center obtains the alarm information, it releases it to the relevant front-line personnel of the tunnel station in time to deal with the fire situation.

The overall structure of the wireless independent smoke fire detector design can include a smoke detection module, control core chip, sound and light alarm module, and wireless transmission module as shown in Figure 5. The smoke detection module monitors the tunnel smoke environment, and the chip module can realize the analog-to-digital conversion of the smoke data. When the smoke data reach the threshold, the alarm needs to be triggered with the assistance of the sound and light alarm module. In terms of the signal transmission technology of the smoke data and detection alarms, the communication protocol can be selected according to the local conditions. For example, Zigbee technology can meet the needs of large-scale and long-distance wireless transmission; however, the signal transmission speed is slow, and it is more suitable for scenarios where signal timeliness requirements are not high. RFID technology has the characteristics of a strong signal diffraction ability and little influence from obstacle interference; 5G technology is particularly suitable for long-distance communication, but the transmission cost is high.

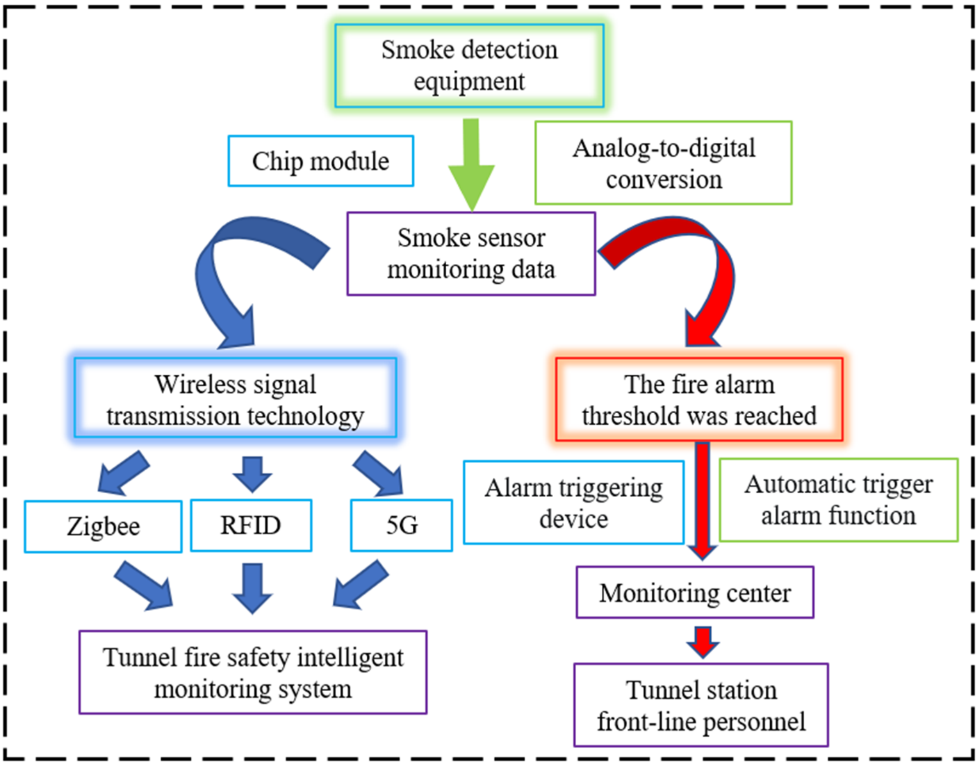

Figure 5. Wireless smoke detection system.

In addition to smoke detection, video monitoring, open fire monitoring, and temperature monitoring in tunnels should also be integrated to comprehensively determine whether there is a fire accident inside tunnels.

2.5. Tunnel Fire Door Monitoring

Tunnel fire doors play a vital role in the tunnel fire and can be used for the timely evacuation of traffic to reduce fire losses. Therefore, it is necessary to monitor the status of the tunnel fire door, including whether the fire door can be opened normally, whether the fire door is damaged, etc. Through the monitoring information, the tunnel management department can obtain the performance status of the fire door in real time. Specifically, by installing the latest wireless sensors, e.g., Zigbee, 5G, radio frequency identification (RFID), and other technologies, the operation status of the fire door is monitored, and abnormal phenomena are detected and alarmed in time.

In addition, the tunnel management personnel need to carry out professional training on a regular basis, such as training regarding to the use and maintenance of the fire door monitoring system, to ensure that, once a fire occurs, the monitoring data can be obtained in time, the fire situation can be accurately judged, the fire door can be safely started and operated normally, and the responsibility can be strengthened so that the intelligent monitoring system can be used correctly to accurately judge the on-site fire disaster situation.

2.6. Real-Time Online Monitoring of Smoke Exhaust Fans

In the daily operation of tunnels, it is necessary to regularly check the performance of the smoke exhaust fans to ensure the normal operation of the smoke exhaust fans and to ensure the safe operation of the tunnels. However, especially for extra-long tunnels, which can be several kilometers in length, the traditional methods for checking the smoke exhaust fans are considered to be time-consuming and laborious, and sometimes there may be omissions and personal errors. Thus, it is highly necessary to use cutting-edge monitoring technologies, e.g., fiber-grating-based or other wireless sensing methods, to achieve the convenient, fast, and real-time performance monitoring of the smoke exhaust fans. When designing this monitoring system, the specific physical quantity can be obtained according to the following formula: the exhaust air volume can be calculated through $E = V \times S$, where V is the wind speed and where S is the cross-sectional area of the tunnel. For a specific tunnel, S is usually a specific value, so the wind speed V is a key indicator. Thus, the key monitoring and detection physical quantity for the smoke exhaust fans can be determined to be the wind speed.

The proposed quasi-unattended tunnel fire safety intelligent monitoring system is especially suitable for tunnels located in remote areas, where the geological conditions are complex and harsh and where the layout of the management facilities along the way is complex. In these cases, the cost of fire safety operations and management is high, and disaster prevention and rescue have a difficult to meet the objective requirements. Therefore, it is urgent to implement quasi-unmanned operations and intelligent remote monitoring. However, for extra-long tunnels, e.g., tunnels of more than three kilometers, or tunnels with more traffic that are prone to accidents, for their safety considerations, it is still necessary to set up manned fire monitoring and processing departments at the tunnel portal, e.g., traditional tunnel management stations and substations. In the event of a fire accident, the staff at the tunnel portal can arrive at the scene of the fire as soon as possible and deal with the fire accident in a timely manner.

3. Tunnel Fire Safety Evaluation and Fire Rescue Plan Based on Monitoring Information

3.1. Tunnel Fire Safety Evaluation Enabled by the Analytic Hierarchy Process

For tunnel fire safety monitoring, the intelligent monitoring system can be firstly established to realize the real-time monitoring of the fire conditions. At the same time, the application software system is established, and the tunnel fire safety evaluation system can be established to realize the real-time evaluation and management of tunnel fire safety; additionally, its core functions include real-time monitoring, an early warning and alarm, data analysis, data management, and fire rescue plan formulation.

Tunnel fire safety evaluations are mainly to find, analyze, and warn about the risk factors and possible hazards in tunnel engineering so as to comprehensively evaluate the possible dangers in the project and to divide the risk grade according to the size of the risk level. In order to make the selected fire safety evaluation indicators sufficiently representative to better reflect the operation safety status of the tunnel, the following should be taken into account: (1) The tunnel engineering safety evaluation system is a complex and interactive system, and the prediction, analysis, and solution of tunnel operation safety problems should take into account the integrity of the system; additionally, the overall thinking should be carried out with the entire engineering system. (2) When establishing a comprehensive evaluation system, the principle of combining a quantitative analysis and a qualitative analysis should be followed, and the corresponding indicators should be further quantified based on the existing qualitative analysis so that the indicators have better measurability so as to objectively represent the specific characteristics of certain aspects of the evaluation object. (3) The content of the indicators selected in the evaluation system should be clear, and the expression meanings of some indicators should not be mixed. In order to ensure the transparency and authenticity of the structural health and safety assessment results, the assessment indicators should be independent at the same level.

In order to ensure tunnel fire safety, scientific and reliable safety evaluation factors and indicators need to be selected. In this study, the analytic hierarchy process was used to establish a hierarchical relationship diagram affecting tunnel fire safety as shown in Figure 6. The diagram divides tunnel fire safety into three factor layers. The topmost factor (level ③) is the "Tunnel fire safety evaluation system", which evaluates the tunnel fire safety level from a macro perspective. Level ② factors include "Accident fire", "Failure of fire-fighting equipment", and "Tunnel environment", and this layer is the main influencing factor of level ③ tunnel fire safety. Then, each level ② influencing factor is connected with its own influencing index represented as level ①. Among them, "Accident fire" is set with three influencing indicators: "Spontaneous combustion of automobiles", "Forest fires", and "Electromechanical fault". "Failure of fire-fighting equipment" has five fire equipment monitoring modules, i.e., "Intelligent monitoring of wireless hydrants", "Power monitoring of fire-fighting hydrants", "Wireless smoke detection", "Wireless water pressure monitoring", and "Wireless water flow monitoring". The specific situation of the tunnel environment is evaluated by the "Tunnel environment" index, which is influenced by the following four factors, e.g., "Smoke exhaust fan performance", "Emergency lighting condition", "Fire door condition", and "Evacuation indicatory sign". Through the intelligent monitoring system of fire safety, the observation value or index parameters for each impact index in level ① can be obtained, and the monitoring method, detection value range, and physical dimension of each impact index are different; therefore, the indicators can be normalized through statistical methods to facilitate the consistency of the fire safety evaluations. Based on the topology diagram in Figure 6, the analytic hierarchy process needs to compare the correlation between the influencing factors in pairs according to the survey or monitoring data and then construct a judgment matrix to solve the weight relationship of the influencing factors.

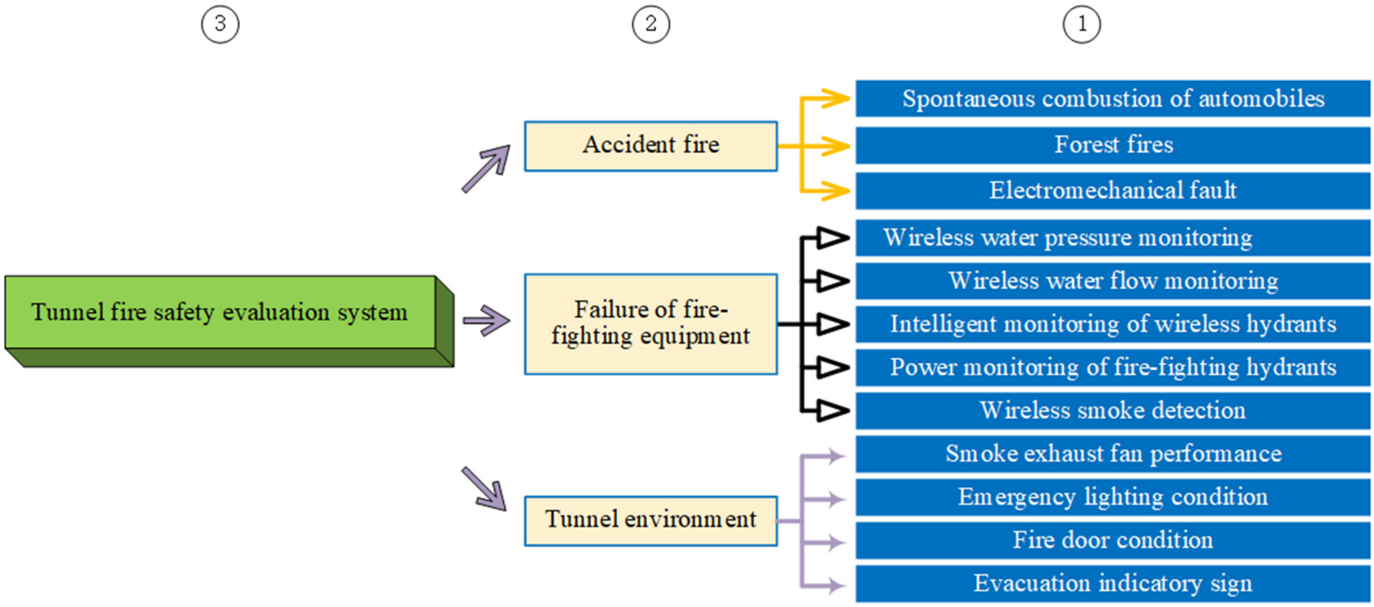

Figure 6. Fire safety evaluation model established by the analytic hierarchy process.

In this study, a fuzzy comment set of the [0–1] interval is established through the change interval of the constructed safety evaluation index parameters. At the same time, considering the relevant technical specifications and standards; referring to the relevant literature, tunnel construction safety management practices, etc.; and combined with the widely used existing grading methods, the degree of tunnel fire safety evaluations can finally be determined to achieve the purpose of tunnel project management and maintenance. Specifically, the tunnel fire safety status classification table can be determined (shown in Table 1) with the help of the tunnel history monitoring data, maintenance norms, standards, and related research literature. The tunnel fire safety status can be roughly classified into five levels; the fire safety level increases from "A" to "E", and, correspondingly, the severity level increases. Finally, according to the fire safety level, the number of firefighters, fire vehicles, fire tools, etc., is intelligently matched to form an adaptive intelligent fire rescue plan.

Table 1. Classification table for tunnel fire safety status.

Fire Safety Status	Rating Range	Overall Responses
A	0.6–1	Maintain normal monitoring and observation
B	0.4–0.6	Maintain normal monitoring and take action
C	0.4–0.3	Needs manual emergency intervention
D	0.3–0.1	Perform manual emergency intervention as soon as possible
E	0.1–0	Perform manual emergency intervention immediately

3.2. Adaptive Fire Rescue Plan Formulation for Tunnel Operations under Quasi-Unattended Background

On the basis of the fire safety intelligent monitoring system, the fire safety evaluation system, tunnel fire safety grading, and the risk management theory, an adaptive fire rescue plan formulation scheme is proposed for quasi-unattended tunnels, and the overall frame diagram is shown in Figure 7. The whole fire rescue plan formulation scheme includes the tunnel fire safety monitoring system, the fire information system, the communication system, and the fire emergency dispatching system, which can effectively carry out real-time fire warnings and rescue plan determination. In this framework, the intelligent monitoring and dynamic warning platform for tunnel operation safety can be developed to perform scientific research and make a judgment on potential fire risk events, to issue accurate early warnings, and to assist fire management personnel in taking proactive traffic control as well as safety prevention and control measures in advance. Among them, the digital fire information system can provide functions, such as the geographic information data and fire scale functions, for the intelligent fire rescue plan formulation system. Through networking with the surveillance system of the public security department, a variety of fire data information can be shared. Actually, the monitoring system is the "eyes" of the fire rescue with the help of the remote monitoring function. In the rescue work, the monitoring system can provide the real-time monitoring of the vehicle driving position, controlled traffic conditions, tunnel structural and operation status, etc. The communication system ensures the information sharing of all the departments in the whole process of the fire rescue and improves the efficiency of cooperation. Fire emergency dispatching can be carried out in accordance with the aforementioned monitoring system and fire safety evaluation system. Generally, the dispatching system in the field of fire protection can be decomposed into a decision-making system and mobile fire-fighting command center. The decision-making system includes the determination of the final fire rescue plan and the concrete implementation process. These four subsystems, including the tunnel fire safety monitoring system, the fire information system, the communication system, and the fire emergency dispatching system, complement each other and cooperate with each other to form a fire rescue plan system under the quasi-unattended background so as to improve the efficiency of emergency rescues and to ensure the safety of tunnel operations.

This study proposes a fire safety intelligent monitoring framework for quasi-unattended tunnels. According to the fire safety monitoring content of these tunnels, the front-end intelligent monitoring system of the tunnels is established to realize the sensing of the fire condition and fire-fighting equipment status inside the tunnels. Furthermore, all kinds of sensor monitoring data in the tunnels can be employed to establish a tunnel fire safety evaluation index system based on which tunnel operation fire safety evaluations can be carried out using the system engineering method, i.e., the analytic hierarchy process. Finally, on the basis of the fire safety level, an adaptive intelligent fire rescue plan can be formed by matching the number of firefighters, fire vehicles, and fire tools through machine learning intelligent algorithms.

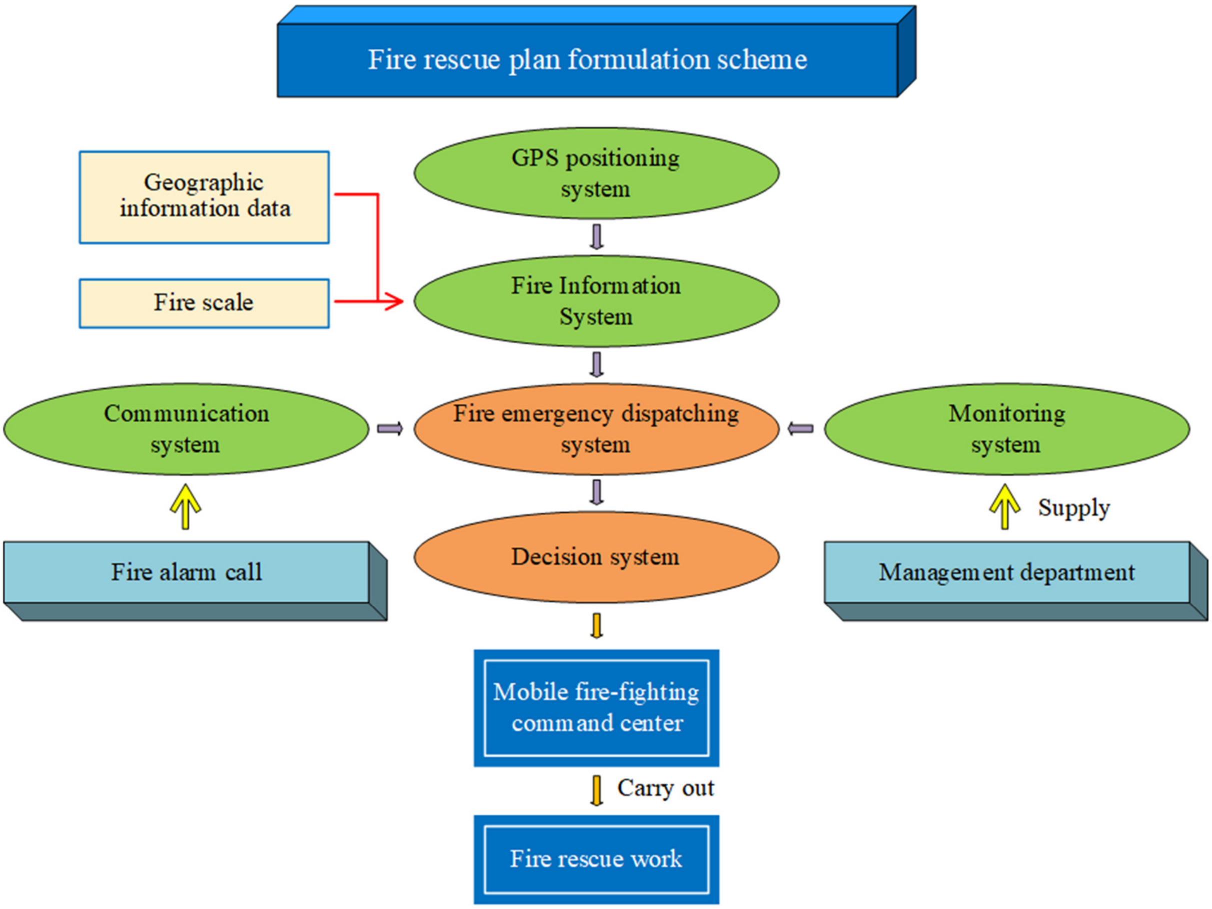

Figure 7. Fire rescue plan framework for tunnel operations.

4. Conclusions

With the higher requirements for tunnel intelligent monitoring and safe operation, this study closely focuses on the realization of a quasi-unattended and intelligent tunnel fire emergency management system so as to provide technical support for the implementation of an unmanned system scheme design as well as tunnel construction and operations. In this study, a quasi-unattended tunnel fire safety intelligent monitoring system is proposed that can realize the comprehensive real-time monitoring of the tunnel operating environment, fire-fighting equipment, and fire status through various monitoring sensors. Then, the tunnel fire safety level can be evaluated based on the monitoring data so as to construct an intelligent fire rescue plan with the incorporation of the monitoring information and safety assessment results. Specifically, this study conducts in-depth research on key supporting technologies such as the wireless intelligent remote monitoring of highly elevated pools, the wireless intelligent monitoring of fire-fighting equipment, a wireless smoke detection system, fire door monitoring, smoke exhaust fan performance monitoring, and the determination of the fire safety evaluation index. Relying on the intelligent monitoring and alarm system for tunnel fire safety, the tunnel operation status monitoring data can be obtained, and the influencing factors are analyzed with the help of the analytic hierarchy process. The AHP model parameters can be evaluated to realize the real-time evaluation and management of tunnel fire safety. The hierarchical model of tunnel fire evaluations was established to carry out the intelligent evaluation of the fire safety level. Finally, an adaptive intelligent fire rescue plan can be formed by intelligently matching the number of firefighters, fire vehicles, and fire tools according to the fire safety level with the aim of providing guaranteed support for the rapid automatic response of tunnel fire protection. In a follow-up study, experiments for model testing and verification will be carried out for the real-world tunnel structures.

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References

1. Gao, S.H. Design of monitoring system for expressway around the city. *China ITS J.* **2007**, *1*, 100–106.
2. Yang, J.Q. Design and Development of Intelligent Maintenance and Detection System for Mechanical and Electrical Facilities of Highway Tunnel. Master's Thesis, Chongqing Jiaotong University, Chongqing, China, 2016.
3. Su, Z.Q. Analysis on intelligent monitoring technology of unattended computer room in highway tunnel substation. *China ITS J.* **2017**, *10*, 137–139. [CrossRef]
4. Peng, J. Intelligent unattended equipment room monitoring system. *Guangdong Highw. Commun.* **2018**, *44*, 196–198.
5. Chen, Z.X. Design of intelligent monitoring and management system for tunnel power distribution room based on internet of things technology. *Mech. Electr. Inf.* **2020**, *23*, 108–109.
6. Qin, X. Analysis on fire prevention and control functions of miniature fire stations. *China Sci. Technol. Inf.* **2020**, *10*, 56+58.
7. Yu, S.J.; Yuan, F.P.; Li, W.C. Present situation of enterprise miniature fire station. *China Public Secur. (Acad. Ed.)* **2019**, *4*, 76–78.
8. Cao, J.J.; Wang, J.P. Innovative design of community micro fire stations. *Design* **2019**, *32*, 16–18.
9. Feng, W.B.; Zhe, G.F. Study on sustainability and construction of micro-volunteer fire station. *J. China People's Police Univ.* **2019**, *35*, 50–52.
10. Bian, H.T.; Zhu, Z.C.; Zang, X.W.; Luo, X.H.; Jiang, M. A CNN Based Anomaly Detection Network for Utility Tunnel Fire Protection. *Fire* **2022**, *5*, 212. [CrossRef]
11. Li, Z.J. Problems and tactics: During the promotion and construction of micro fire station. *Fire Prot. Today* **2021**, *6*, 27–28.
12. Du, Y.L. Research on the Reliability of Highway Tunnel Power Supply System. Master's Thesis, Chang'an University, Xi'an, China, 2013.
13. Wang, Q.B. Discussion on power supply design of freeway. *Technol. Highw. Transp.* **2002**, *3*, 91–93.
14. Su, D.L.; Guo, Z.Y.; Li, Z.Y.; Zhou, Y.F. Operation Risk Model and Monitoring-warning System of Expressway Tunnels. *Transp. Res. Procedia* **2016**, *14*, 1315–1324. [CrossRef]
15. Yang, T.B.; Han, Z.Z.; Li, Z.; Wan, X.J. Economic analysis of prefabricated "prefabricated cabin" temporary facilities in substation engineering. *China Manag. Inform.* **2020**, *23*, 135–136.
16. Luo, J. Research on Safety Operation and Management Countermeasures of Qinling Zhongnanshan Highway Tunnel. Master's Thesis, Chang'an University, Xi'an, China, 2012.
17. Nellen, P.M.; Frank, A.; Broennimann, R.; Sennhauser, U.J. Optical fiber Bragg gratings for tunnel surveillance. In Proceedings of the SPIE's 7th Annual International Symposium on Smart Structures and Materials, Newport Beach, CA, USA, 6–9 March 2000; Volume 3986, pp. 263–270.
18. Wang, Q.A.; Zhang, C.; Ma, Z.G.; Ni, Y.Q. Modelling and forecasting of SHM strain measurement for a large-scale suspension bridge during typhoon events using variational heteroscedasic Gaussian process. *Eng. Struct.* **2021**, *251*, 113554. [CrossRef]
19. Wang, Q.A.; Dai, Y.; Ma, Z.G.; Wang, J.F.; Lin, J.F.; Ni, Y.Q.; Ren, W.X.; Jiang, J.; Yang, X.; Yan, J.R. Towards high-precision data modeling of SHM measurements using an improved sparse Bayesian learning scheme with strong generalization ability. *Struct. Health Monit.—Int. J.* **2023**, 14759217231170316. [CrossRef]

20. Wang, Q.A.; Wang, C.B.; Ma, Z.G.; Chen, W.; Ni, Y.Q.; Wang, C.F.; Yan, B.G.; Guan, P.X. Bayesian dynamic linear model framework for SHM data forecasting and missing data imputation during typhoon events. *Struct. Health Monit.—Int. J.* **2022**, *21*, 2933–2950. [CrossRef]
21. Wang, Q.A.; Zhang, C.; Ma, Z.G.; Jiao, G.Y.; Jiang, X.W.; Ni, Y.Q.; Wang, Y.C.; Du, Y.T.; Qu, G.B.; Huang, J. Towards long-transmission-distance and semi-active wireless strain sensing enabled by dual-interrogation-mode RFID technology. *Struct. Control Health Monit.* **2022**, *29*, e3069. [CrossRef]
22. Wang, Q.A.; Dai, Y.; Ma, Z.G.; Ni, Y.Q.; Tang, J.Q.; Xu, X.Q.; Wu, Z.Y. Towards probabilistic data-driven damage detection in SHM using sparse Bayesian learning scheme. *Struct. Control Health Monit.* **2022**, *29*, e3070. [CrossRef]
23. Zeng, L.; Shaofei, W.; Hui, L. Fire disaster reduction and emergency management of long highway tunnels. *Chin. J. Undergr. Space Eng.* **2012**, *8*, 1584–1590+1625.
24. Zhan, W. Research on Traffic Safety Protective Technology of Long and Large Tunnel Group Area in Mountain Highway. Ph.D. Thesis, Zhejiang University, Hangzhou, China, 2013.
25. Zhang, Y. Study on Traffic Accidents Emergency Control Emergency Plans Model in Freeway Tunnel. Master's Thesis, Chang'an University, Xi'an, China, 2015.
26. Erd, M.; Schaeffer, F.; Kostic, M.; Reindl, L.M. Event monitoring in emergency scenarios using energy efficient wireless sensor nodes for the disaster information management. *Int. J. Disaster Risk Reduct.* **2016**, *16*, 33–42. [CrossRef]
27. Xuan, Y.H. Analysis and Evaluation on Operation Safety of the Long Highway Tunnel. Master's Thesis, Shijiazhuang Railway University, Shijiazhuang, China, 2017.
28. Zhang, W. Analysis on the emergency command system of long tunnels. *China ITS J.* **2018**, *9*, 122–126. [CrossRef]
29. Qian, C.; Chen, J.X.; Luo, Y.B.; Li, S.G. Random Forests-Based Operational Status Perception Model in Extra-Long Highway Tunnels with Longitudinal Ventilation: A Case Study in China. *J. Adv. Transp.* **2018**, *2018*, 5056284. [CrossRef]
30. Wang, J.H.; Sun, Y. Study on Fire Emergency Strategies of Long and Large Tunnel in Expressway. *Value Eng.* **2020**, *39*, 85–87. [CrossRef]
31. Xiao, S. Research on Operational Safety Risk Assessment and Control Technology of Expressway Long Tunnel. Master's Thesis, Chang'an University, Xi'an, China, 2020. [CrossRef]
32. Zhang, F. Research on Safety Management and Evaluation of Expressway Tunnel Fire Engineering. Master's Thesis, Kunming University of Science and Technology, Kunming, China, 2021. [CrossRef]