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Development and Application of Fire Video Image Detection Technology in China's Road Tunnels

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Abstract

A large number of highway tunnels, urban road tunnels and underwater tunnels have been constructed throughout China over the last two decades. With the rapid increase in vehicle traffic, the number of fire incidents in road tunnels have also substantially increased. This paper aims to review the development and application of fire video image detection (VID) technology and their impact on fire safety in China's road tunnels. The challenges of fire safety in China's road tunnels are analyzed. The capabilities and limitations of fire detection technologies currently used in China's road tunnels are discussed. The research and development of fire VID technology in road tunnels, including various detection algorithms, evolution of VID systems and evaluation of their performances in various tunnel tests are reviewed. Some cases involving VID applications in China's road tunnels are reported. The studies show that the fire VID systems have unique features in providing fire protection and their detection capability and reliability have been enhanced over the decades with the advance in detection algorithms, hardware and integration with other tunnel systems. They have become an important safety system in China's road tunnels.

Keywords: Road Tunnels; Fire Safety; Fire Detection; Video Image Detection Technology.

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1. Introduction

In order to cope with the rapid growth of vehicle traffic and limited real estate, a large number of highway tunnels, urban road tunnels and underwater tunnels have been constructed throughout China over the last two decades. The statistics show that 15,181 road tunnels were constructed in China at the end of 2016, and the total length of the road tunnels have increased from 628 km in 2000 to 14,039.7 km in 2016 [1]. In addition, the complexity and length of the urban road tunnels constructed have also significantly increased. As of the end of 2016, there are 3,520 road tunnels stretching between 1 km to 3 km with a total length of 6045.5 km, and 815 tunnels longer than 3 km with a total length of 3,622.7 km [1]. Some examples of long tunnels in China include the Beiheng Tunnel in Shanghai (10 km long) and the Zizhi Tunnel being constructed in Hangzhou (13.9 km long). At the same period of the time, the traffic in China's tunnels has also significantly increased. The average daily traffic in some of road and underwater tunnels of cities, such as Shanghai, Nanjing and Zhongqi, has reached to 150,000 in 2017.

One of negative consequences with the increase in number of tunnels and traffic is that the fire incidents in China road tunnels, especially incidents involving loss of life, have substantially increased. For example, the Huishan Tunnel

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incident in Wuxi resulted in 24 deaths (2010), Rock Tunnel incident in Shanxi caused 31 dead (2014) and the Tao Jiakuang Tunnel incident in Shantong had 12 deaths (2017). The data collected from research papers, incident data collecting systems, network news reports and related reports from the Chinese transportation departments show that nearly 160 cases of large and medium-sized tunnel fire incidents have occurred from 2000 to 2017 [2]. The analysis on incident data indicates that more than 16 per cent of the fire accidents in the China's road tunnels have led to casualties, and more than 24.8 per cent accidents resulted in the damages of the tunnel structure and facilities [2]. The loss of life and property caused by fire incidents in China's tunnels is higher than those in developed countries [3].

Fire detection is a key element for fire protection in road tunnels. It provides warnings of a fire incident, activates ventilation systems, fire suppression systems and emergency systems, and aids in directing evacuation and firefighting operations. Detection can make a significant difference between a manageable fire and one that gets out of control [4-5]. There are many types of the fire detection system that are available for use in road tunnels, including linear heat detection systems, flame detectors, video image fire detection systems, smoke detection systems and spot heat detectors, etc. [5-7]. Among these technologies, the fire video image detection (VID) has been regarded as an emerging technology and demonstrated unique features in providing fire protection in tunnels. It can detect all fire types according to either flame or smoke characteristics produced from a fire. It processes multiple spectral images in real time to detect a fire at greater distances in short times, and at the same time, it can identify the location of a fire, track and monitor its growth and spread, and guide evacuation, rescue and firefighting. The fire VID systems have been widely used to provide protections for large constructions, transportation, industrial and military facilities [8-14]. Over the past ten years, VID technology has gradually been introduced in China's road tunnels, playing an important role in improving fire safety.

This paper analyzes the challenges of fire detection in China's road tunnels. The capabilities and limitations of fire detection technologies currently used in China's road tunnels are discussed. The research and application of VID technology, including various detection algorithms, evolution of VID systems from a manual one to an automatic fire detection system, distributed fire detectors and an integrated fire/traffic/security detection system in road tunnels, as well as performance of these systems in various tests are reviewed. Some cases involving VID applications in China's road tunnels are reported.

2. Challenges of Fire Detection in China Road Tunnels

As required by China Standards and Codes [15], the road tunnels with the length of 1,000 m or longer must be equipped with fire detection systems. However, unlike other applications, challenges for use of fire detection systems in the tunnels are significant. The fire incidents in tunnels are attributed to increased traffic, careless driving behavior, vehicle failure, inadequate tunnel management, inadequate safety rules on vehicles, the length and complexity of the tunnels, and the specific features of tunnel infrastructure [2]. Various fire types, sizes, locations and causes could be encountered in the tunnels. The fire incidents in the China's road tunnels can be divided into three major categories: vehicle failure, vehicle traffic accidents, and other factors [2, 16, 17]. Figure 1 shows a detailed breakdown of the causes of these tunnel fire incidents, including:

- 70 per cent of fire incidents started from vehicle failure, which includes: 22 per cent from vehicle engine fires, 18 per cent from vehicle tire fires, 16 per cent from spontaneous combustion of vehicle itself, 7 per cent from vehicle loaded goods fire, and 7 per cent from electric circuit fires;
- 18 per cent of fire accidents accounted from vehicle crash;
- 12 per cent of accident fires from the unknown causes.

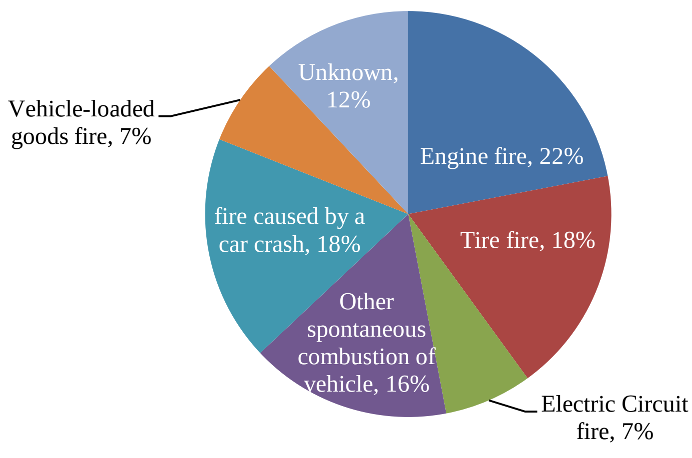

Figure 1. Analysis of fire accidents in China road tunnels

The most of fires in China's road tunnel are involved in the common commute cars with heat release rate (HRR) ranging 3-5 MW, which is consistent with the tunnel fires occurred in other countries [18]. However, when heavy goods vehicles or buses with the HRR of 20-30 MW or higher are involved, the consequence of the fire accidents in tunnels are very severe. Once the incident has occurred, the fire developed and spread very quickly in the tunnel, even led to explosions of delivered goods in some accidents [16-22]. The fire incidents also produced large amounts of hot and toxic smokes. They spread very quickly and very far in narrow space of tunnels with assistance of strong winds, resulting in quick loss of visibility and exacerbating the disaster. Due to the complexity and length of the tunnels, it becomes very difficult for people to evacuate and be rescued during the accidents. The disasters in tunnels become increased in the scale with time and can last longer without effective fire control and firefighting. In addition, the traffic congestion due to accidents in tunnels can result in more disasters occurring, such as multi-vehicles crashing and/or involving fires.

Considering the difficulties in rescue and firefighting in tunnels, urban tunnels and underwater tunnels with length of 1500 m or longer in China are required to equip with automatic fire suppression system [15]. The tunnel is divided into multiple fire suppression zones, each measuring at 25 m in length. During a fire incident, the fire suppression system is activated at two adjacent zones. It is required that the fire detection system must be able to accurately identify the fire location and activate the fire suppression at the correct zones for quick fire control, and at the same time, to avoid any fault discharge during daily operation, resulting in traffic congestion in the tunnels.

The environments in road tunnels are very harsh. Exhaust fumes from vehicles in the tunnels are dirty and partly corrosive. The lighting conditions in tunnels are very complex, such as the changes of light in day and night, various tunnel light sources, various vehicle lights, light and sun reflections and shadows. There are various moving vehicles with different sizes and velocities. In addition, the tunnel has strong fluctuating air with ventilation speed ranging from 0 to 5 m/s or higher. The temperature in the tunnel can significant change in daily and by season. For example, over the last few years, the air temperatures in urban road tunnels in some southern regions of China reach over 60 degrees Celsius in summer, and drop to -10 degrees Celsius in winter, increasing the possibility of faults for vehicle and fire detection systems. It is very challenge for fire detection systems to sustain and work well in harsh tunnel environments with low nuisance alarms.

As a result, International Road Tunnel Fire Detection Research Project [23] suggested that there are generally three performance criteria for the application of a fire detection system in tunnels. The first criterion is their detection capabilities. It is expected that the fire detection systems shall be able to detect various fire types at their early stage under challenged incident conditions, and simultaneously locate the fire incident. It is also desirable that the fire detection system be able to provide fire information and communicate well with other fire protection systems regarding the spread, growth and scale of fire and smoke in the tunnels, and aid in directing evacuation and firefighting operations. The second performance criterion requires that the fire detection should be reliable and not be affected much by the location of the fire in the incidents, the emissions of pollutants from vehicles and blowing ventilation air. The third criterion is that the fire detection system should work properly in harsh tunnel environment with limited maintenance requirements and their nuisance alarm rate should be established at an acceptable level.

Maciocia reported that there are eleven detailed performance requirements on linear heat detection systems in road tunnels, including [5]:

- Detection accuracy (1-2ºC for absolute temperature measurement, 0.5ºC for rate-of-rise temperature measurement and ±5m for out of a 50 m tunnel segment);
- Detection time (30-60 s);
- System approval;
- System interface to other systems;
- Fault tolerance;
- Fail- and false-alarm-safe operation (no false alarm);
- Repair time;
- Tunnel washing machine;
- System life time;
- Operation cost; and
- Maintenance cost.

Some of these requirements for fire detection have been adopted in China's standards [15, 24].

3. Existed Fire Detection Technologies in China Road Tunnels

Before 2010, the fire detection technologies that were mainly used in China road tunnels were linear optic fiber heat detection systems, linear fiber grating heat detection system and two-spectrum infrared (IR) flame detectors.

Both linear optic fiber and fiber grating heat detection systems respond to a fire accident based on the rate of temperature rise or pre-set alarm temperature [25-28]. Linear heat detection systems are a popular one used in the tunnels. Each sense cable of the system is required to cover two traffic lanes in the tunnels. Many researches have been conducted to study their capability and limitation in tunnel environments [29-32]. Test and operation results show that the linear heat detection systems:

- Respond to a fire at its flame stage as the temperature in the tunnel raises, which may miss early warnings of the fire, depending on the fire type. Their detection times are determined by fire type, size and location in the tunnel and could be delayed when the fire is shielded or under longitudinal airflow. One 1m^2 of gasoline pool fire is usually used to evaluate the detection capability of the linear heat detection systems installed in China's tunnels.
- Can identify the fire location along the cable. However, the fire position identified could have a big difference from the real one as hot spot near the ceiling of the tunnel is shifted under strong wind conditions.
- Have relatively low nuisance alarms. Defective manufacturing quality in the fiber grating heat detection systems can lead to nuisance alarms.

Dual IR flame detectors respond to a fire accident by detecting the flame radiations produced from the fire [25, 33, 34]. Their maximum detection distance ranges from 40 to 50 m in the tunnels. Their performances in tunnel environments have also been substantially investigated [31, 32, 35]. Test and operation results show that flame detectors:

- Respond to a fire at its flame stage, which may miss some early warnings of the fire, depending on the fire type. Some are mainly designed for gasoline and diesel fires, not to other fire types, such as heptane fires. They do not respond to fully shielded fires, as the radiations produced are blocked. Their detection times are determined by fire type, size and location in the tunnel and are delayed when the fire is shielded or under longitudinal airflow.
- Can identify the region where the fire is located, but not the fire position in the region. Unclear or wrong information on fire location could be provided when a large fire is detected at the same time by a few flame detectors located nearby the fire source.
- Have relatively low nuisance alarms, but lens of the detectors can be easily contaminated as they face on-coming vehicles, and work in dirty, humidity and smoke-filled environments.

In addition, both linear heat and flame detection technologies can only provide limited fire information on the fire scale, growth and spread in the tunnel. As a result, these detection systems are usually required to work together with the Closed Circuit Television (CCTV) system in the tunnels.

Authority in Shanghai in 2013 investigated the functions of the fire protection systems in 13 urban road tunnels built from 2003 to 2010, in which either linear heat detection systems or IR flame detectors were equipped with [36]. It was found that some of fire detection systems did not work efficiently, some had high malfunction and nuisance alarm rates, while others could not even correctly respond to a fire incident. The successful cases for timely and correct response to vehicle fire incidents occurred in urban road tunnels in Shanghai were limited. As a result, the fire suppression systems in tunnels were not activated automatically by the detection systems but manually.

4. Research and Development of Fire Video Image Detection Technology

In order to compensate for the deficiencies of the linear heat detection systems and optical flame detectors, fire video image detection (VID) technology has gradually been introduced in China's road tunnels over the past ten years. The video image system itself is an essential system used for traffic management and security protection in the tunnels. Cameras and corresponding facilities required in the video monitoring system are already standard features of road tunnels.

The original video image technology for fire detection was intended to transfer or record video images and then present them to the human for fire identification. However, with the increase in the tunnel length involving many cameras, it is hard to manage and process numerous video images on time only relying on human's justification. The automatic fire VID system is a combination of video cameras, computing, and video image analysis software [8, 25]. A typical process of an automatic VID system in fire detection includes digital image inputs from cameras, data filtering processing, background learning and modeling, physical characteristics analysis, data fusion, alarm probability calculation and output. One or multiple frames are put on the suspicious flame or/and smoke signs during detection. Pattern recognition and image processing logic are used to analyze the images on the fly. Fire alarms are issued, once the characteristics of flame and smoke are identified.

There are three types of fire VID systems that are commercially available: the flame, smoke and flame/smoke VID systems [37]. Flame-based VID systems detect a fire based on the flame characteristics produced by the fire, such as flaming colour, shape, frequency, chromatic aberration and intensity. Smoke-based VID systems detect a fire mainly based on the smoke characteristics, such as smoke shape, movement, colour, and blurring. Flame/smoke-based VID systems detect all fire types, according to either the smoke or flame characteristics of the fire.

Over the last two decades, efforts have been made to study the characteristics of flame and smoke as well as nuisance sources encountered in tunnel environments, develop various flame and smoke detection algorithms, and evaluate performance of fire VID systems in lab and operational tunnels. With advance in technologies, fire VID has been evolved from an automatic fire detection system, to a distributed fire detector and an integrated fire/traffic/security detection system in road tunnels.

4.1. Fire Detection Algorithms

Color information of the fire was used for fire detection in the early studies of VID system. Chen et al. [38] used raw R, G and B color information and developed a set of rules to classify the fire pixels. Noda et al. [39] analyzed the relationship between temperature and RGB pixel channels and used gray level histogram features to recognize fires. Phillips et al. [40] used the Gaussian-smoothed color histogram to generate a color lookup table of flame pixel and to identify the fire pixel based on temporal variation of pixel values. Celik et al. [41] developed a statistical color-model in video sequences. However, the fire pixels cannot be segmented well from other objects that have the similar color distribution as fire. This could lead to high rate of false alarms. In order to enhance the reliability for fire detection, various flame detection algorithms based on the features of not only the flame color, but also their patterns, motions, flicker and edge blurring were proposed. For example, the flame detection algorithm proposed by Rong et al. [42] included a generic color model, the geometrical independent component analysis model, the cumulative geometrical independent component analysis model and BP neural network based on multi-features of the flame patterns. Celik's detection algorithm was consisted of a flame color modeling and motion detection [43]. The clues used in Toreyin et al.'s fire detection algorithm [44] included flame ordinary motion and color, flame and fire flicker, quasi-periodic behavior in flame boundaries, color variations in flame regions, and irregularity of the boundary of fire-colored regions. Xuan et al. [45] divided their flame detection algorithm into four stages: (1) an adaptive Gaussian mixture model to detect flame moving regions; (2) a fuzzy c-means (FCM) algorithm to segment the candidate fire regions from these moving regions based on fire color; (3) special parameters extracted based on the flame temporal and spatial characteristics; and (4) a support vector machine to distinguish the fire from non-fire. The studies conducted by Wong and Fong indicated that the Otsu multi-threshold algorithm integrated with Rayleigh distribution analysis (modified segmentation algorithm) can be used to produce clear flame only images, while the Nearest Neighbour algorithm can be used to detect flame and non-flame images [46].

The visual characteristics of smoke are less trenchancy and more complicated in comparison to the flame. Yuan developed an accumulated model with block motion orientation for smoke detection [47, 48]. Ko et al. [49] used both motion detection and color information of the smoke for fire detection. In order to distinguish smoke from mist, Wei et al. [50] used a multi-spectral image system to obtain image sequence in specific spectral range of the smoke and mist. Millan-Garcia et al. [51] proposed a smoke detection algorithm in which the motion and color of the smoke are analyzed, the isolated blocks are eliminated through morphologic operations and non-smoke regions are discarded based on the expansion property of the smoke with time. Muhammed et al. proposed an early fire detection method for both indoor and outdoor fires by using convolutional neural networks that had five convolutional layers, three pooling layers and three fully connected layers [52].

For application of fire VID technology in road tunnels, Wieser and Brupbacher [9] proposed a smoke detection algorithm. Their approach was based on a loss of contrast in the imaged caused by the presence of smoke. For simplicity, they only considered the luminance contrast in their algorithm. They conducted fire tests at the test tunnel Hagerbach with heat release rate up to 5 MW and wind speed between 0.5 and 5 m/s, calibrated the smoke in a smoke box, and conducted alarm tests with large scale tunnel fires in the road tunnel "Schonberg", as well as environmental tests in Gubrist tunnel. They reported that the algorithm was quick to detect smoke, and at the same time immune to false alarms during a short period of operation in tunnels.

Jamee, etc. investigated the use of video image processing for early fire detection in tunnels in their European UPTUN program [53]. They conducted a literature review on the algorithms used for fire detection in tunnels. The performance of two commercial and one academic VID systems was evaluated. It was found that tens of false alarms from these systems were produced in less than a week due to traffic queues, reflections of the sue on the entrance of the tunnel. They studied the characteristics of flame and tunnel light sources. The fire detections in static images with segmentation techniques, and shape and contour analysis techniques were analyzed. Their research results suggested that these image processing techniques are not sufficient for fire VID in harsh environments. They further considered the time-dependent behavior of fire objects, and developed tracking and track-based algorithms. No smoke detection algorithm was studied in their program.

Neural network is also used to determine presence of the flame and smoke in the fire VID algorithm. Ono et al proposed a method to use neural network to analyze the video images for flame detection in road tunnels [54]. The flame images were taken from the dynamic image, and the estimated flame zone was extracted by the labelling method. After standardizing the flame zone by expansion and reduction, quantiles of its histogram and area were calculated as feature parameters of flame. The fire was finally judged by the hierarchical type neural network (one input layer, one middle class and one output layer) with the feature parameters (color and area information) as input elements. The flow chart of their image processing is shown in Figure 2. Their test results showed that the vehicle fire in tunnels was detectable by application of the neural network.

Yu et al proposed a method by using a back-propagation neural network for smoke detection [55]. The color and motion features of the smoke are used as input elements for the neural network in their algorithm. The neural network was trained to determine the presence of the smoke. Experimental results showed that the proposed approach was able to distinguish the smoke from non-smoke videos, and its accuracy was depended on the selected statistical values for training of the neural network.

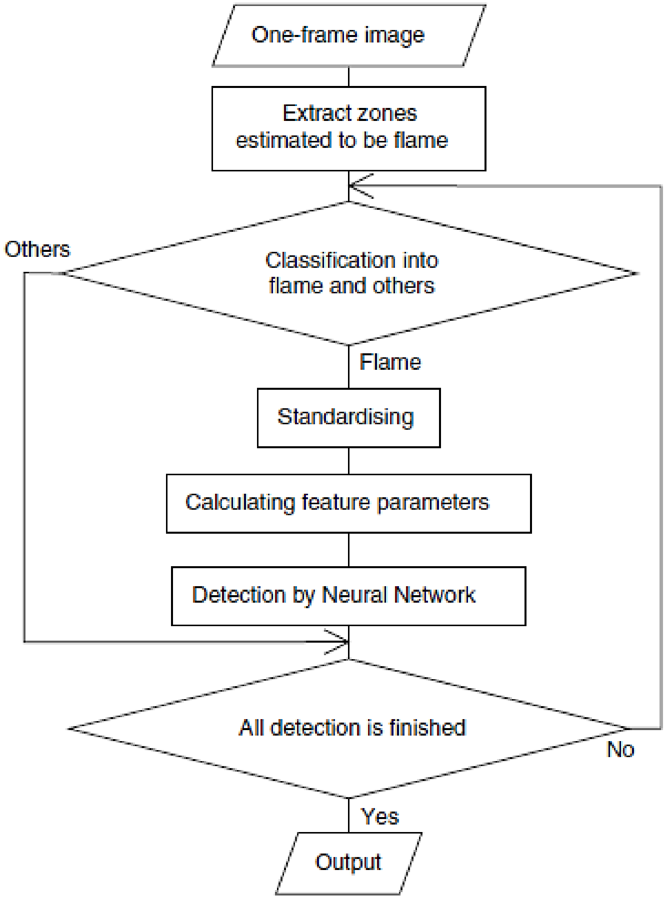

Figure 2. The flow chart of image processing proposed by Ono et al. [54]

In order to reduce the false alarm rate and make the detection more reliable in road tunnels, Han and Lee developed a flame and smoke detection method [56]. Their detection algorithm consisted of two internal algorithms: Flame and Smoke Detection Algorithm. Various tunnel and vehicle lights and non-smoke region were eliminated first, and then the identified flame and smoke regions were extracted in their algorithm, as shown in Figure 3. The performance of the proposed fire detection method was evaluated in the lab, and the flame and smoke regions were exactly detected, but no test results in operational tunnels were provided.

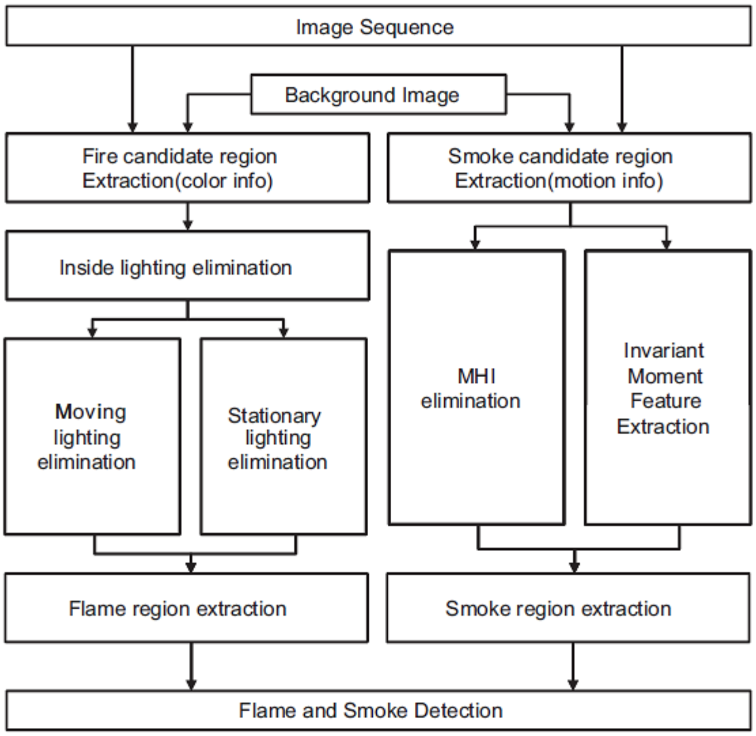

Figure 3. VID algorithm proposed by Han and Lee [56]

Both smoke and flame are generated during most of fire incidents. Yu, Mei and Zhang proposed a real-time detection algorithm to improve the detection reliability by detecting both flame and smoke at the same time [57]. In addition to using color features, the dynamic features of the fire, such as turbulent movements, changeable shapes, growing rate and oscillation, were considered in their algorithm. The fire detection was processed into four major phases: 1) moving pixels and regions were extracted from the image using frame differential method; 2) two color models were used to find flame and smoke candidate regions; 3) foreground accumulation images were built of both flame and smoke; 4) motion features of flame and smoke were calculated based on block image processing and optical flow technique. Their detection method was tested in various conditions, including in tunnel environment, demonstrating good reliability as the features of both flame and smoke were processed and detected.

4.2. Evolution of Fire VID Technology

The fire VID system designed for flame and smoke detection is the first system that was introduced for use in the tunnel environments. It is consisted of a few of video cameras, a computer unit with video analysis software and display monitors. The cameras up to 8 sets are together connected to the computer unit in which video images from cameras are processed and analyzed using alarm algorithm (Figure 4).

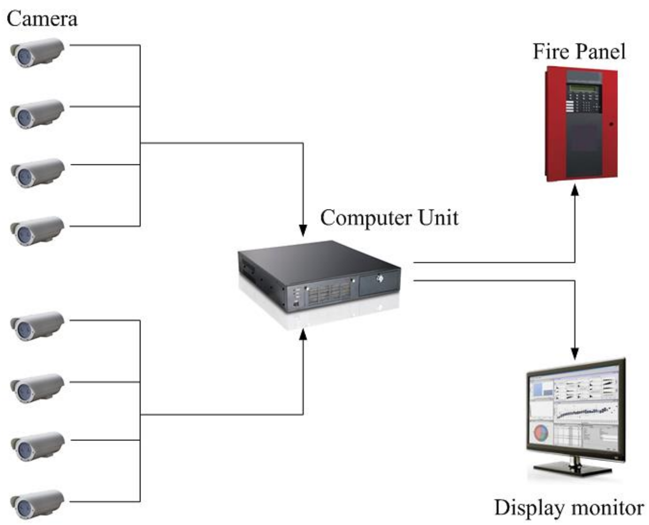

Figure 4. Schematic of a fire VID system

The fire VID systems are mainly used in short tunnels involving a limited number of cameras. They are not suited for long tunnels equipped with many cameras due to the difficulty in the process and management. It is difficult for the system to provide information on the fire position in a monitoring region. In addition, there are also concerns on the reliability of the system. Since the cameras are connected and processed in one computer unit, any malfunction of the computer unit would lead to failure of the system.

With advance in digital camera and computer technologies, the distributed fire VID detector has been developed and widely used over the last ten years [14, 58, 59]. It is an independent fire detector in which both the video processing and alarm algorithm execution are performed at the detector. The detectors are directly connected to display monitors or to control panels for providing fire protection. They are easily manageable, more reliable and flexible to use in comparison with the fire VID system.

High quality cameras used in the VID detectors provide high definition images. Some of distributed VID detectors are equipped with two cameras, one regular and one IR camera, as well as an IR light source, as shown in Figure 5 [14]. With both color/black and IR images, more information on the fire source is provided, and the characteristics of the flame and smoke are also more clear, sharp, and distinguishable from the background during image processing. They can reduce nuisance alarms caused from lightings, sunlight and moving vehicle lights in tunnels, and enhance the capability to detect fires inside and underneath the vehicle. The detector with the IR light source is able to work at dark to detect smokes.

Figure 5. Photo of a distributed fire VID detector [14]

The VID detectors equipped with two cameras are also able to accurately provide information on the fire position in monitoring zones. It is determined according to the location of the flame, not the spread of smoke in the tunnel. As shown in Figure 6, the distance between flame source and the detector is calculated based on the principle of binocular stereo vision [60], where P is fire source, O_l and O_r are left and right cameras of the detector, T is the distance between the camera, and Z is the distance to the detector from fire source. This is an important feature for the fire detection system to correctly activate local ventilation and fire suppression systems for fire protection and to provide guidance for the evacuation from the tunnel during a fire incident.

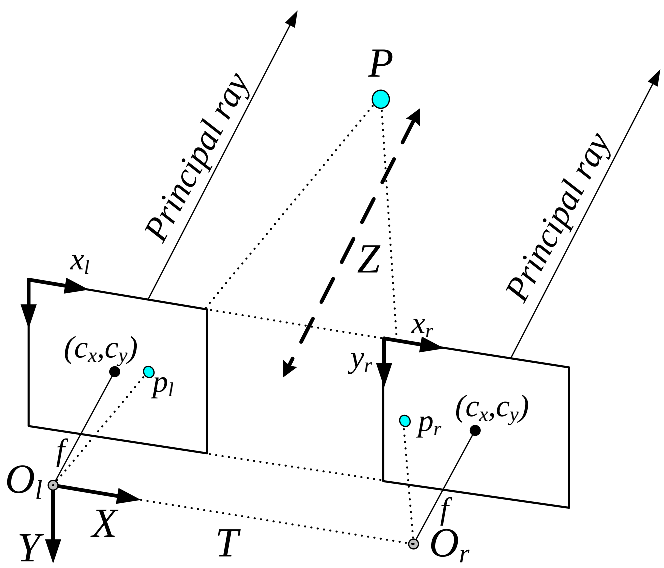

Figure 6. Schematic for identification of a fire position in the tunnel in a VID detector with two cameras

Currently the fire detection system, traffic management system, and security protection system are usually three independent systems in the tunnels. There is limited communication among these systems. However, many fire incidents in tunnels are initiated from security or traffic incidents due to vehicle fault or crash, bad driving behavior, inadequate rule on vehicles. Limited communication among these systems could lead to delay for providing early fire alarms and protection, resulting in the failure in preventing the loss of life and property from the fires in tunnels. Efforts are being made to combine three independent fire detection, traffic management and security protection systems into one system [61]. As shown in Figure 7, one kind of such integrated system used in China's tunnels is that the distributed VID detectors are used to monitor traffic, security and fire incidents at the same time. The VID detector still directly functions as fire detection and is connected to the fire protection system, while images associated with traffic and security incidents that are provided by the VID detector are processed at a traffic/security analyses and manage unit. The information on traffic, security and fire incident is shared, and communicated and managed together in the system. Once an incident occurs, the integrated VID system can efficiently respond to it, and prompt early fire warning through monitoring and tracing traffic and security accidents. The integrated system can also largely reduce the costs of tunnel facilities and their maintenance. With further advance in technologies, information on the traffic, security as well as fire detection can be analysed and processed at the VID detector.

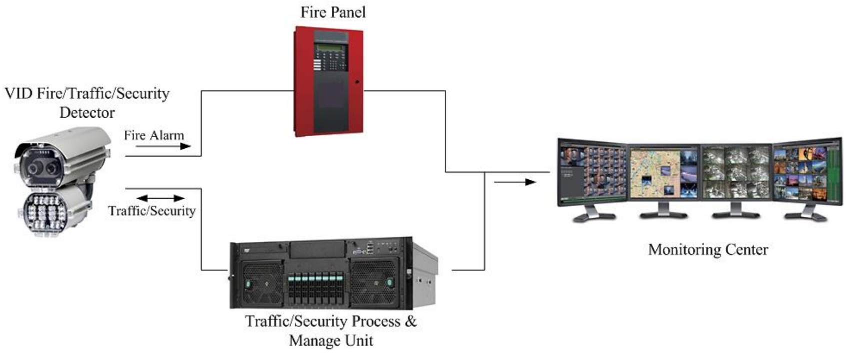

Figure 7. Schematic of an integrated fire/traffic/security VID system

4.3. Evaluation of Performances of VID Systems in Tunnels

International Road Tunnel Fire Detection Research Project developed a test protocol to evaluate the performance of fire detection systems for use in road tunnels in a two-year international research project [7]. The fire scenarios selected are those common and challenged ones encountered in tunnel fire incidents, including:

- Pool fires located inside, underneath and behind vehicles with HRR up to 3.5 MW;
- Stationary passenger vehicle fires with HRR up to 2 MW; and
- Moving vehicle fires with HRR up to 150 kW.

The longitudinal wind speed in the tests are ranged from 0 to 3 m/s. It is also required that fire detection systems are installed and operated in an operational road tunnel for one year.

The capability and limitation of two fire VID systems together with other detection technologies were evaluated in NRC research program [31, 32, 62-65]. Full-scale fire tests were conducted in a laboratory tunnel in Ottawa and in the Carré-Viger tunnel in Montreal, Canada (Figure 8). The reliabilities of these detection systems, including the nuisance alarms and maintenance requirements in smoky, dirty and humid tunnel environments, were investigated in the Lincoln Tunnel in New York City for one year (Figure 9).

Figure 8. Fire tests in the Carré-Viger tunnel in Montreal, Canada [32]

Figure 9. Environmental tests in the Lincoln tunnel in New York, USA [65]

The extensive research showed that unlike other types of fire detection technologies, the fire VID systems could respond to a fire at its smoldering stage for early fire alarm, detect all fire types according to either flame or smoke characteristics produced, but they had no response to the moving fires at the speed of 20 km/hour in the tests. The impact of obstacles and winds on the performance of the fire VID fire system was limited. The fire tests also showed that the effect of smoke on the visibility of the cameras was determined by the fire scale, ventilation conditions, camera location and geometry size of the tunnels. The fire VID system could provide valuable and real-time fire information on fire location, growth and spread. Environmental tests in the tunnel showed that during operation, the fire VID systems had substantial nuisance alarms caused by some traffic lights, such as flashing lights on service/utility vehicles, or weather conditions causing fouling of camera window, or the reflection of sunlight into the tunnel entrance [65].

The performances of fire VID detectors and integrated fire/traffic/security VID systems in fires and tunnel environments were substantially investigated in a number of China road tunnels, including a mock-up of Shanghai Yangzi River Road Tunnel [59], a laboratory tunnel in Zhangzhou, Fujian [66], operating Xianyue Mountain road tunnel in Xiamen [58] and Zhongnan Mountain road tunnel in Shanxi [68]. The fire scenarios and test protocols used in these tests were similar to those developed by National Research Council Canada (NRC) in the NFPA tunnel research project [7], but the detection distances from fire VID detectors to fire sources ranged from 45 to 210 m in the tests, which was much longer than those in NRC tests. The speed of longitudinal wind in the tests was up to 5.5 m/s. In addition, more fire tests simulating the smoldering fires occurred in the vehicles were conducted (Figure 10). The effect of harsh tunnel environments and nuisance sources on the capability of the VID detectors and integrated VID systems were investigated, including contaminated cameras, flashing lights on the service/utility vehicles, headlights, brake lights and reflection of traffic lights on the tunnel wall. The tests for traffic and security management included inverse driving, careless driving behavior, congestion management, fallen or left objects from vehicles, abnormal pedestrian behavior, etc.

Figure 10. Smoke fire tests in Xianyue Mountain road tunnel in Xiamen [67]

The test results from the more than 100 fire tests conducted in laboratory and operating tunnels in China demonstrated that performances of the fire VID detectors in detecting all fire types and providing early fire warnings were similar to those in NRC research project. With the advance in technologies, however, newly developed fire VID detectors had much longer detection distance than previous ones. They detected a $0.4m^2$ of gasoline pool fire under 5.5 m/s of wind speed at 31 s from 125 m of the distance [67]. They were able to accurately identify fire locations in its detection region without position shift. This is an important feature of fire detection for correctly activating the fire suppression system, as the detection region of a fire VID detector covers a number of fire suppression zones. The detection times of fire VID detectors generally increase with an increase in detection distance and wind speed.

Environmental tests in the tunnels showed that the effect of contaminated camera windows on the response of the fire VID detectors to the flaming fires was limited, but they did make the detectors being more difficult to respond to smoke. With an adjustment of detection view and location of the detectors as well as update of alarm algorithm on the traffic lights, the number of nuisance alarms were reduced.

Test results on traffic management also showed that the integrated fire/traffic/security VID systems were able to calculate the number of moving vehicles and monitor vehicle congestion. It could recognize inverse driving and stopped vehicles and identify suspicious fallen or left objects from vehicles (Figure 11). It was also able to provide information on drivers and pedestrians, automatically track their movement, and prevent them from entering into prohibited areas (Figure 12). The system could immediately notify monitoring personnel for traffic accidents, any abnormal traffic and human behavior, and trespassing and/intrusion [66, 67].

Figure 11. Test of integrated VID system on incident identification and left object from a vehicle in Xianyue Mountain road tunnel in Xiamen

Figure 12. Test of integrated VID system on pedestrian behaviour in Xianyue Mountain road tunnel in Xiamen

5. Cases on Applications of Fire VID Technology in China Road Tunnels

Information obtained from the extensive fire and environmental tests has assisted at optimizing technical specifications, performance criteria, guidelines and installation requirements of fire VID technologies for tunnel applications. The studies have also been used to update NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways [68] and a number of China’s Standards, including China's National Standard "Design Specifications of Automatic Fire Alarm System" GB50116-2013, China Industry Standard "Highway Tunnel Design Code" JTGD70-2014 as well as China's National Standard "Technical Specifications for Fire Protection in Road Tunnels” that will be implemented in 2018 [15, 24, 70].

With understanding of the fire VID technology as well as the recognitions from the end users and fire safety authorities, fire VID detectors and their combinations with other types of detection system have been gradually introduced to provide fire detection in the urban road tunnels, two-way long highway tunnels and underwater tunnels in

China. More than 30 Chinese road tunnels are equipped with fire VID detectors and integrated fire/traffic/security VID systems over the last few years and more tunnels are being planned to install.

One recent application of the distributed fire VID detectors is in the Honggu Tunnel in Nanchang, Jiangxi. It is the largest immersed tunnel among country's underwater tunnels. The length of the tunnel is 2650 m for Northern line and 2665 m for the southern line. Its cross section is 30 m in width and 8.3 m in height. Its fire detection system is consisted of the fire VID detectors and a linear fiber grating heat detection system. The fire VID detectors are installed at 4.5 to 5.2 m high from the ground and the distance between detectors is 40 to 100 m far, depending on the geometry of the tunnel. A total of 88 detectors are used in the tunnel. The layout of each fire VID detector is coordinated with corresponding fire suppression zone. During a fire incident, the fire location and activation of the fire suppression system are determined by the VID detectors according to the flame detected, not by smoke detected, avoiding any fault discharge. The detectors provide information on not only the spread range and scale of the fire and smoke, but also the distance between the fire location and tunnel outlets for evacuation, rescue and firefighting. The detectors are regularly cleaned and maintained. Figure 13 is the displays of fire VID detectors in the Honggu Tunnel.

Figure 13. Display of fire VID detectors at Honggu Tunnel in Nanchang, Jiangxi

One example for application of the integrated fire/traffic/security VID detection systems in urban tunnels is Xianyue Mountain Tunnel in Xiamen that was operated in 2012 year. It is a two-way tunnel with the length at 1071.78 m for the east tunnel, and at 1095.89 m for the west tunnel. The cross section of each tunnel is 9.25 m wide and 6.7m high. The integrated VID detection system is consisted of eighteen distributed fire VID detectors, one traffic management and accident identification unit, and one central monitor and display system. The distributed VID detectors are used to monitor traffic, security and fire incidents. They are installed at 4.7 m high from the ground and the distance between detectors is 100 to 125 m far, depending on the geometry of the tunnel. Figure 14 is the schematic of the integrated VID system used in the Xianyue Mountain Tunnel. The integrated system has been running smoothly since 2012. As a result, four other urban tunnels in Xiamen are also equipped with the integrated VID detection systems and more installations are being planned.

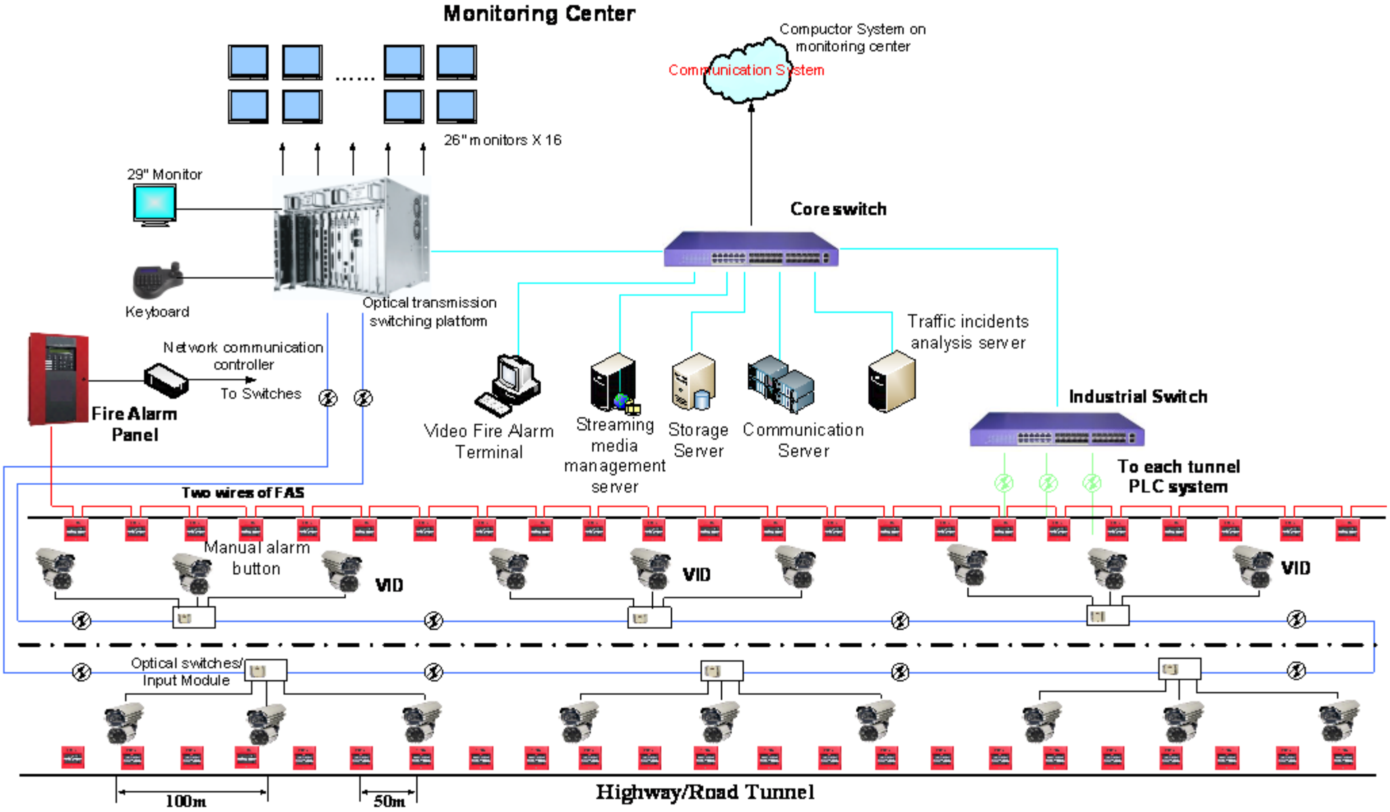

Figure 14. Schematic of integrated fire/traffic/security VID system at Xianyue Mountain tunnel in Xiamen, Fujian

6. Conclusion

China is facing significant challenges of fire safety in road tunnels due to large increase in traffic and the number of urban, underwater and highway mountain tunnels built on its roads. Fire detection is a key element for fire protection in road tunnels, which can make a significant difference between a manageable fire and one that gets out-of-control.

Fire VID technology is regarded as an emerging fire detection technology and has demonstrated unique capabilities in detecting all fire types based on either flame or/and smoke produced at their early stage. They can detect a fire at a long distance, and provide real-time images and information on fire growth, spread and scale to provide guidance for evacuation, rescue and firefighting.

The VID detectors that are equipped with regular and IR cameras are able to enhance their detection capability and reduce nuisance alarms caused from lightings, sunlight and moving vehicle lights in tunnels, as the characteristics of the flame and smoke captured are more clear, sharp, and distinguishable from the background during image processing. The VID detectors with two cameras can also locate a fire position in monitoring zones for activating local ventilation and fire suppression systems.

One major concern on the usage of fire VID technology is its reliability and the number of nuisance alarms produced in harsh road tunnel environments. Various fire detection algorithms considering the characteristics of smoke, flame as well as nuisance sources have been proposed. The neural network is also used to determine presence of the flame and smoke in the detection algorithms. The reliability of the VID systems in tunnel environments have been improved over the years and will be further enhanced with understanding of characteristics of fires and nuisance sources, and advance in artificial intelligence.

The fire VID technology has evolved from a manual to automatic VID system, distributed VID detectors as well as integrated fire/traffic/security VID systems over the last decades. The evolution in VID technology has enhanced its detection capability and reliability. It also reduces the costs of tunnel facilities and their maintenance. The integration of fire detection with traffic manage and security in road tunnel is still a developing system. With further advance in electronic technologies, information on the traffic, security as well as fire detection will be able to be analyzed and processed at a distributed VID detector.

The test protocol for evaluating the performance of fire detection systems in the road tunnels was developed. Extensive fire and environmental tests on various fire detection systems, including VID systems have been conducted. These tests are very important for understanding of the performance of VID systems and for optimizing their technical specifications, performance criteria, guidelines and installation requirements in tunnel environments. With the recognitions from the end users and fire safety authorities, the application of fire VID systems in road tunnels in China has substantially increased over the last decade. They are now playing important roles in providing fire safety for road tunnels.

7. Conflicts of Interest

The authors declare no conflict of interest.

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