

Intelligent Identification of Water Accumulation and Ice Formation in Traffic Tunnels

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Abstract: Water accumulation and ice formation in traffic tunnels pose prominent safety hazards (e.g., reduced road friction, increased traffic accidents) and threaten structural integrity (e.g., damage to waterproof layers and lining structures). Therefore, the intelligent identification of these two hazards is crucial for safeguarding traffic safety and optimizing tunnel maintenance strategies. The intelligent identification system integrates computer vision, deep learning, and multi-source sensor data fusion technologies. Current state-of-the-art practices adopt deep learning models for target segmentation and detection, combined with robust image preprocessing and post-processing techniques. This technology exhibits significant practical application value, and its continuous innovation and development are expected to substantially enhance the level of tunnel safety management and structural durability preservation.

Keywords: Intelligent recognition; Traffic tunnel; Water accumulation and ice formation; Deep learning; Computer vision

Online publication: February 27, 2026

1. Introduction

As a critical component of modern transportation networks, traffic tunnels play an irreplaceable role in ensuring the efficiency of daily travel and the stability of regional economic development^[1,2]. However, affected by factors such as complex geological conditions, extreme weather, and operational wear, water accumulation and ice formation frequently occur in traffic tunnels, seriously endangering their safe and unobstructed operation. Thus, the research and application of intelligent identification technology for water accumulation and ice formation in traffic tunnels have important practical significance and engineering value.

Water accumulation in traffic tunnels is caused by multiple factors. During the rainy season, excessive precipitation may exceed the drainage capacity of the tunnel, leading to surface waterlogging; in addition, malfunctions or blockages in the tunnel's internal drainage system can also result in water accumulation^[3]. Accumulated water not only reduces the friction coefficient of the road surface, prolongs vehicle braking distances, and increases the risk of traffic accidents such as rear-end collisions and skidding but also has a persistent adverse

impact on the tunnel's waterproof layer. As the core barrier against groundwater erosion, the waterproof layer is prone to aging, degradation, and even failure when immersed in water for a long time^[4]. Once the waterproof layer loses its function, groundwater directly contacts the tunnel lining, accelerating the process of concrete carbonation, steel bar corrosion, and structural cracking, thereby threatening the long-term stability of the tunnel structure.

Ice formation in traffic tunnels mainly occurs in cold seasons. When the internal temperature of the tunnel drops to or below the freezing point and the air humidity reaches a certain level, the accumulated water on the road surface is prone to freezing^[5]. The icy road surface has extremely low friction, which significantly increases the difficulty of vehicle control and poses a severe threat to traffic safety, similar to driving on an ice sheet. At the same time, ice formation can cause damage to tunnel supporting facilities: for example, low temperatures may lead to freezing and bursting of water supply and drainage pipes, failure of electrical equipment, and other problems, thereby affecting the normal operation of the tunnel^[6].

The damage caused by water accumulation and ice formation to traffic tunnels involves both traffic safety and structural safety, and the damage mechanism is complex and cumulative^[7]. Therefore, it is urgent to develop efficient and accurate intelligent identification technology to realize real-time monitoring and early warning of these two hazards, providing reliable technical support for scientific prevention and control and targeted maintenance.

2. Principles of intelligent identification technology

In the traffic tunnel environment, the intelligent image recognition technology for water accumulation and ice formation is a key means to prevent traffic accidents (e.g., vehicle skidding, loss of control) and realize timely maintenance. Its technical system integrates computer vision, deep learning, and professional image processing technologies^[1]. The core principles, key technologies, and common tool chains of the system are detailed as follows.

2.1. Core principles: Distinction based on visual features and environmental context

The intelligent identification of water accumulation and ice formation relies on the significant differences in visual features between the two hazards and the surrounding road environment, combined with environmental context information for comprehensive judgment^[9].

2.1.1. Visual feature characteristics of water accumulation

The visual features of water accumulation are as follows:

- (1) Reflective properties: The water surface has a mirror-like reflection effect, which can reflect light sources such as vehicle headlights, tunnel lighting, and ambient light, forming obvious highlight areas in the image. The shape, brightness, and position of these highlight areas change dynamically with the viewing angle of the camera and the direction of the light source, which is one of the most distinctive features for identifying water accumulation;
- (2) Color properties: Clear water is colorless and transparent. In images, when the water layer is thin and the reflection effect is weak, it often presents a darker shade relative to the road surface; when affected by the surrounding environment, it may be tinged with environmental colors. Murky water contains sediment and other impurities, usually showing yellowish or brownish tones;

- (3) Texture properties: Flowing water has obvious ripple and wave textures; static water has a relatively smooth surface, but there may be slight ripples or reflection interference. The edge of the water accumulation area is irregular and has no fixed shape;
- (4) Dynamic properties: Water is fluid. In continuous video sequences, the reflection points and edge contours of the water accumulation area will change continuously with time, showing obvious dynamic characteristics.

2.1.2. Visual feature characteristics of ice formation

The visual features of ice formation are as follows:

- (1) Reflective properties: The ice surface also has reflective characteristics, but compared with water, its reflection is more “hard” and directional. The highlight areas are usually more uniform and diffuse, or form regular specular reflection patterns. Thin ice presents a translucent state, and the reflection effect is relatively weak;
- (2) Color properties: Clear ice is transparent or semi-transparent, and its color in the image is highly consistent with the road surface, making it difficult to distinguish directly; thick ice often shows bluish-white or grayish-white tones. Dirty ice mixed with impurities such as mud presents earthy colors similar to mud;
- (3) Texture properties: The ice surface is extremely smooth, without the ripple texture of water. The edge of the ice formation area is relatively sharp, and it is often distributed in patches. Frosted ice or melting ice may show granular or honeycomb-like micro-textures;
- (4) Dynamic properties: Ice is a solid substance. In short-term video sequences, its shape and position remain relatively stable unless it is in the process of melting or continuous formation.

2.1.3. Environmental context auxiliary judgment

The information is as follows:

- (1) Location information: Water accumulation and ice formation have obvious location aggregation characteristics. They often occur in road depressions, near drainage outlets, tunnel entrances and exits (where temperature changes sharply and ice formation is easy), and under seepage points ^[10];
- (2) Temperature information: By integrating temperature sensor data, when the road surface temperature is close to or below 0°C, the detected moist areas are highly likely to be ice or in a state of impending freezing, which can effectively improve the accuracy of ice formation identification;
- (3) Weather information: Combined with external weather data, the probability of water accumulation and ice formation in tunnels increases significantly after rainfall or snowfall. Weather factors can provide important prior information for the identification model ^[5].

2.2. Key technologies and methods

2.2.1. Image preprocessing

Image preprocessing is the foundation of intelligent identification, aiming to eliminate noise and interference in tunnel images and enhance the effective features of water accumulation and ice formation ^[1]. Aiming at the problems of uneven illumination, low brightness, and strong glare in tunnels, technologies such as histogram equalization, Retinex algorithm, and deep learning-based low-light enhancement are adopted to adjust the image

brightness and contrast, ensuring the consistency of image quality under different illumination conditions. The strong light generated by vehicle headlights in the tunnel is easy to be misidentified as the reflection of water accumulation or ice formation. For this problem, a combination of image inpainting and deep learning algorithms is used to accurately segment and repair the glare area, eliminating false positive interference. For slight camera shake caused by vehicle vibration or environmental factors, image stabilization processing is performed through frame alignment and motion compensation technologies to ensure the stability of feature extraction in continuous frames.

2.2.2. Feature extraction

Feature extraction is the core link of identifying water accumulation and ice formation, which is divided into traditional visual feature extraction and deep feature extraction^[8]. Before the popularization of deep learning, traditional visual features were widely used in target identification and are still used as supplementary means in specific scenarios. By converting images into HSV, Lab, and other color spaces, the color distribution characteristics of water accumulation and ice formation areas are analyzed. For example, the saturation (S) and brightness (V) channels in the HSV space can effectively distinguish the color differences between water, ice, and dry roads. Using Gray-Level Co-occurrence Matrix (GLCM), Local Binary Patterns (LBP), Gabor filters, and other technologies to extract texture information of the target area, so as to distinguish the ripple texture of water, the smooth texture of ice, and the rough texture of the road surface.

Using Canny edge detection and other algorithms to extract the edge contours of water accumulation and ice formation areas, and determine the scope of the target area through the shape characteristics of the contours. By detecting the highlight areas in the image, analyzing their shape, area, and brightness distribution, the reflection characteristics of water and ice are distinguished. As the current mainstream and most effective feature extraction method, Convolutional Neural Networks (CNNs) are used to automatically learn multi-level and multi-dimensional feature representations from raw images^[9]. Through the hierarchical convolution and pooling operations of the network, low-level features (e.g., edges, textures) and high-level semantic features (e.g., overall shape, reflection mode) are extracted, which can accurately distinguish water accumulation, ice formation, and dry road surfaces.

2.2.3. Object detection and segmentation

Object detection and segmentation realize the positioning and pixel-level classification of water accumulation and ice formation areas^[1]. For instance:

- (1) Object detection: The goal is to determine whether there are water accumulation and ice formation in the image and output their bounding boxes. Currently, deep learning-based detection models such as YOLO (You Only Look Once) are mainly used. These models require a large number of annotated tunnel water and ice images for training to ensure the accuracy and real-time performance of detection;
- (2) Semantic segmentation: By classifying each pixel in the image, the water accumulation area, ice formation area, dry road surface, and other background areas are accurately labeled at the pixel level. Models such as U-Net are widely used in tunnel defect segmentation due to their excellent performance in small target segmentation, which can provide precise spatial location information for subsequent hazard assessment.

2.2.4. Dynamic analysis (video sequences)

For video data, dynamic analysis technology is used to further improve the reliability of identification^[10]. By calculating the motion vector of pixels between consecutive frames, the motion pattern of the target area is analyzed. Flowing water will generate irregular optical flow fields, while static ice will not produce obvious motion vectors (or only move synchronously with the camera). Using frame differencing technology to detect newly appearing water accumulation and ice formation areas; establishing a background model of the tunnel road surface to identify changes in existing hazard areas (e.g., expansion of water accumulation, melting of ice formation). It should be noted that modern deep learning models usually integrate feature extraction, object detection/segmentation, and classification into an end-to-end network structure, which simplifies the technical process and improves the efficiency and accuracy of identification.

2.3. Common tool chains

The implementation of intelligent identification technology relies on mature software and hardware tools. The main tool chain includes as listed:

- (1) Programming language: Python is the main development language, which has rich image processing and deep learning libraries;
- (2) Image processing library: OpenCV is used for image preprocessing operations such as illumination adjustment, edge detection, and glare removal;
- (3) Deep learning framework: TensorFlow and PyTorch are used for model construction, training, and deployment, supporting the rapid development of detection and segmentation models;
- (4) Deployment platform: Edge computing platforms (e.g., NVIDIA Jetson series) are used for on-site real-time processing of tunnel image data, reducing the delay caused by cloud transmission and ensuring the real-time performance of early warning.

3. Conclusion

The intelligent image identification of water accumulation and ice formation in traffic tunnels is a complex technical system that comprehensively applies computer vision, deep learning, and multi-sensor fusion technologies. Its core principle is to fully leverage the differences in reflective, color, texture, and dynamic characteristics between water accumulation and ice formation, combined with environmental context information such as location, temperature, and weather, to achieve accurate identification of hazards. At present, the mainstream technical route is based on deep learning semantic segmentation (e.g., U-Net) and object detection models (e.g., YOLO), combined with efficient image preprocessing (e.g., illumination adjustment, glare removal) and post-processing technologies to improve the accuracy and robustness of identification. The tool chain is mainly composed of Python, OpenCV, TensorFlow/PyTorch, and edge computing platforms, which provides a mature technical foundation for the engineering application of the system. In conclusion, the intelligent identification system for water accumulation and ice formation in traffic tunnels has important practical significance and broad application prospects. With the continuous advancement of deep learning technology and the improvement of multi-source data fusion capabilities, the identification accuracy, real-time performance, and adaptability of the system will be further enhanced, which is expected to play a more critical role in ensuring traffic safety and extending the service life of tunnel structures.

Disclosure statement

The author declares no conflict of interest.

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