"Human-Vehicle-Tunnel-Environment" Based Study on Key Issues and Solutions of Operation and Maintenance Risk Evaluation for Urban Road Tunnels

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Abstract: This paper provides analyses of operating environment features of urban tunnels in building, traffic, hydrology, vertical alignment, social environment and examination of key issues in operation and maintenance risk evaluation for urban tunnels: diversity and complexity of evaluation factors; timeliness of evaluation result; uncertainty of rating, etc. Relevant countermeasures are proposed for the above-mentioned key issues, including information collection technology based on the Internet of big data technology and risk dynamic assessment and management platform, etc., to provide a solution path for the real-time, intelligent and informatization of urban tunnel risk management and control.

1. Introduction

By the end of 2018 China had completed a total of 1000 urban tunnels[1]. As cities grow the number and length of urban tunnels will keep increasing. Urban tunnels are normally surrounded by dense buildings and interwoven roads, and traffic mix in the tunnel is complex. In the event of an accident, its consequences will surely be more severe. It is therefore necessary to evaluate operation and maintenance (O&M) risks for in-service urban tunnels.

Some research has been done on operation risk evaluation for urban tunnels. Gu Yin[2] selected urban tunnel structure, E&M system and operation system to establish evaluation indicators and system and developed a fuzzy algorithm specifically for urban tunnel operation management. Through analysis of abrupt and cumulative damages to tunnels, Wu Hao[3] presented a tunnel safety forecast and alarm architecture. Guo Zhongyin and Dai Youhua[4] investigated driving behavior features in tunnel (group) sections and developed an identification method based on risk and feature points. Overall, research on urban tunnel operation risk evaluation is still inadequate with a lack of clear understanding of the key issues in risk evaluation.

In this paper we analyze the features of urban tunnel operating environment from multiple dimensions and describe key issues in operation risk evaluation. On this basis, we propose pertinent countermeasures for management of urban tunnel operation risks to provide support and assistance for improved urban tunnel safety in the future.

2. Features of Urban Tunnel Operating Environment

2.1. Interact with other buildings
When passing under the city a tunnel will inevitably come into spatial conflict with building foundation, water pipelines and power lines. This complicates the operating environment of urban tunnels and increases operation risks. In addition, construction activity around the tunnel will also result in tunnel deficiencies such as differential settlement, cracking and water seepage.

2.2. Traffic features
Compared with ordinary tunnels, urban tunnels have the following features: as part of urban roads, they carry higher traffic volumes and experience more frequent congestion and car following; due to speed restriction, vehicles typically move at low speeds inside urban tunnels; the mode of transport is dominated by cars for passenger transport with a low proportion of large trucks; traffic flow peaks and wanes at fixed times in a day.

2.3. Hydrological environment
Populous cities in China tend to be located near mountains and rivers[5], and such cities often have an urgent need for underground road/rail. When an urban tunnel crosses a river, or near a water system has to withstand huge water pressure in addition to earth pressure or surrounding ground pressure, making water seepage or leakage more likely than ordinary highway tunnels. Consequently, urban underwater tunnels require a higher ability to resist pressure and seepage than ordinary tunnels.

2.4. Vertical alignment
To facilitate drainage ordinary tunnels typically are designed with a herringbone vertical or a unidirectional slope alignment [6] whereas most urban tunnels pass beneath surface buildings due to restrictions by other structures. To connect to surface road, urban tunnels usually have a U-shaped profile. In the event of heavy rainfall and the road drainage system being overloaded, vast amounts of water tends to flow into the tunnel, compromising its structural safety and even causing traffic accidents.

2.5. Social environment
Due to high traffic flow and high attention from the public, accidents in urban tunnels attract much attention from the public. Meanwhile, high sensitivity of the general public and a lack of knowledge on tunnel safety often amplify the risk of the event itself.

3. Key Issues in Urban Tunnel Evaluation

3.1. Complexity and diversity of risk evaluation factors
Due to a combination of factors, considerations for urban tunnel O&M risk are more complex, making risk evaluation more difficult. It is therefore necessary to classify and summarize these risk factors. In this section, based on "human-vehicle-tunnel-environment" we divide urban tunnel risk evaluation factors into four categories (fundamental factors, traffic factors, equipment factors and environmental factors), as follows:

①Fundamental factors of urban tunnels.
Fundamental factors mean hard-to-change properties of the tunnel after completion: tunnel configuration, tunnel structure and social value. See Fig 1.
② Traffic factors:
Traffic is a major function provided by the tunnel. It is embodied not only in vehicles themselves but also in the mutual relationship between vehicles and the tunnel. Therefore, traffic factors are divided into vehicle factors and traffic characteristics of vehicles passing through the tunnel, as illustrated in Fig 2.

③ Equipment factors.
Equipment factors mean various facilities required to ensure safety operation of the tunnel, including operation infrastructure, monitoring equipment, alarm facility and emergency rescue equipment, as illustrated in Fig 3.
Environmental factors:
Environmental factors include both the operating environment inside the tunnel and natural environment outside the tunnel. They have a positive or negative on tunnel safety. See Fig. 4:

Management factors:
Tunnel management factors come either directly from tunnel operator's safety organization or from promotion by security laws, safety information, etc. as illustrated in Fig 5.

3.2. Timeliness and limitations of tunnel operation risk evaluation
Overall, existing problems in current urban tunnel risk evaluation and management are characterized by emphasis on qualitative evaluation while lacking quantitative evaluation, emphasis on staged evaluation while lacking understanding of the big picture and emphasis on static evaluation while lacking dynamic evaluation, as detailed below.

① Most evaluation focuses on risk status in a long period with a lack of timeliness.

Existing structural risk evaluation for operating urban tunnels is mostly based on detection data for tunnel O&M while traffic risk evaluation is mostly based on long-term statistics of traffic flow at long intervals. Such evaluations can only provide a general understanding of tunnel operation risks and cannot timely identify tunnel risks or assess current safety status of the tunnel.

② Limitation due to undiversified evaluation dimension.

Most existing tunnel operation risk identification and evaluation focus on certain aspects, lacking real-time monitoring equipment for individual vehicles, a technical system for identification and evaluation of tunnel operation risks, and overall and systematic considerations. They are unable to provide an overall understanding of tunnel operation safety.

3.3. Complexity in determining risk rating
The root cause of the complexity of risk evaluation is its intrinsic subjectivity and complexity. The subjectivity originates from insufficient cognition of human and irrational action: the different cognizant abilities of the evaluators will lead to different evaluation results. The complexity comes from differences in the environment in which a tunnel is located (risk evaluation focuses on different aspects for underwater urban tunnels and ordinary urban tunnels), criticality of tunnel subsystems and facilities (the evacuation cross passages in a long tunnel are given a bigger weight than those in a short one) and the level of acceptable risk in different regions in the event of an accident (tunnels receiving more attention have a bigger social impact).

4. Management and Control Measures for Urban Tunnel Operation Risk
At present, technologies for monitoring tunnel traffic, structure, environment, etc. are increasingly mature and enable real-time understanding of tunnel operating status. However, there is a lack of means to monitor risks during operation in real time; relevant data are collected without comprehensive analysis. Using real-time monitoring and control means, big data analysis technology and IoT technology we set up an urban tunnel operation risk evaluation and management system to provide real-time, intelligent and IT-based management and control of urban tunnel risks.
4.1. IoT and big data based information acquisition technology

4.1.1. Acquisition of tunnel apparent deficiency data. The apparent deficiency long-term monitoring equipment is a long-term integrated monitoring system based on IoT to monitor cracking, water leakage and spalling of operating tunnel linings. It uses video processing technology to select an appropriate gray threshold for segmentation of monitored deficiency images, extract feature edges and dynamically monitor deficiency development according to gray levels in different stages of development.

This system provides non-contact monitoring, good reliability and range, high level of integration and the ability to simultaneously monitor crack, water leakage, pavement damage and pavement luminance. Fig 6 illustrates the architecture of the apparent deficiency long-term monitoring system.

4.1.2. Acquisition of traffic data. Real-time traffic monitoring information and forecast data are acquired through the vehicle monitoring and identification system and third-party map platforms. Analyses of the above data allow the ability of real-time evaluation and forecast of traffic risks.

①Vehicle monitoring and identification system

Based mainly on machine vision technology and through a certain number of cameras arranged inside the tunnel, the tunnel vehicle monitoring and identification equipment allows dynamic capture and storage of such parameters as lanes, speed, type of vehicle, time headway and number of vehicles. Its working principle is described below:

- Locating vehicles in sections

By interfacing with the in-tunnel video monitoring system, the proposed system automatically divides the tunnel into several monitoring sections based on camera monitoring points when vehicles enter the tunnel and locates the vehicles according to monitoring information from each section to achieve real-time tracking and monitoring of vehicles in the tunnel, as illustrated in Fig 7.

![Fig 6. Schematic architecture of the apparent deficiency monitoring system](image-url)
Identification of vehicle type

The vehicle type identification system is developed on the basis of AI model engine and intended to provide service logic data classification. This system can identify 5-seat cars, 7-seat minibuses, trains, buses, coaches, hazardous chemical vehicles (tankers), concrete mixer trucks, container trucks and special vehicles.

Vehicle license plate recognition

It is based mainly on AI model engine and OCR technology. The AI model engine calculates through a model the plate location information to be entered in key frame, the logic layer gets the image through location information and OCR technology allows extraction of text information from the image.

Speed recognition

Speed recognition is based mainly on \( V = \Delta d / \Delta t \) where \( \Delta t \) can be directly obtained from fixed frame time of the video and \( \Delta d \) is calculated from displacement pixel difference. Its principle is illustrated in Fig 9.
Lane recognition
Based on AI model engine the lane recognition technology uses a certain number of lane images to train the model in lane recognition and then to detect lanes in real time through lane feature data.

Data management
Data management includes management of vehicle type data, camera data (mounting location, height and pixel, etc.) and other data. Video data are stored on the video server and some of them is cached in the system which will remove redundant video data periodically.

Third-party map platform
Real-time traffic condition information is accessed through JavaScript API provided by Amap. The platform requests URL through HTTP, receives and parses returned HTTP data (JSON or XML) to obtain real-time traffic condition information.

4.1.3. Acquisition of meteorological data. The platform visits the API provided by CIMISS, requests URL and parses returned JSON data to obtain meteorological data.

4.2. Dynamic risk evaluation and management platform for urban tunnels in complex environment

4.2.1. System composition. The urban tunnel risk evaluation information system is developed under B/S architecture. Its back-end is written mainly in Python; back-end data processing and Web API are realized in conjunction with Django framework. Its front-end is developed under Vue framework.

Main components of this system are visualized dynamic risk evaluation management, diversified data acquisition management, operating tunnel structure monitoring management, E&M equipment monitoring management, tunnel operation accident data management, real-time vehicle monitoring management and risk evaluation data management back-end. Its architecture is illustrated in Fig 10.
4.2.2. Key technology.

①Extraction of information for accident database: operating tunnel accident data are acquired by python crawler based data acquisition tools. Python-based crawlers can visit mainstream news media websites at fixed times such as MicroBlog, Sina News and Tencent News, fetch data on tunnel operation safety accidents using keywords such as "tunnel", "accident", "traffic" and "disaster" and store these data in the database.

②Creation of urban tunnel hazard and deficiency knowledge bases: the risk hazard database is created by identifying hazard goals by means of social environment analysis, external project environment analysis and facility interior environment analysis, and then through classification by system safety theory and function analysis theory; the deficiency knowledge base is created based on
expert consultation, analysis of deficiencies during construction and investigation of existing deficiencies.

③ Dynamic risk evaluation technology for urban tunnels: tunnel fundamental factors (tunnel configuration, civil facilities, etc.), equipment factors, traffic factors, environmental risk factors and management factors are used as evaluation indicators; then the weight of each indicator is determined by AHP and fuzzy mathematics theory; finally the overall tunnel risk value is determined through fuzzy synthetic evaluation model.

4.2.3. System functions. This system is able to manage tunnel fundamental data, operation accident data, operation monitoring data and vehicle monitoring data and evaluate tunnel operation risk, as detailed below.

① Tunnel fundamental data management. This function provides the ability to manage tunnel fundamental data and equipment information including adding, modifying and deleting data on a given tunnel.

② Operation accident data management. This function provides the ability to manage tunnel accident data and statistically analyze accident features.

③ Operation data monitoring management: this function provides the ability to acquire data on the tunnel itself and surroundings including monitoring of tunnel E&M equipment, tunnel structure, environmental data and traffic data.

④ Vehicle monitoring management includes monitoring of historical vehicle data, real-time vehicle data and prioritized vehicles. Historical vehicle data are used for storage and query of historical information on vehicles moving into and out of the tunnel, including license plate, vehicle type and average speed inside the tunnel. Real-time vehicle data are used for real-time query of information on vehicles inside the tunnel and in each section. Prioritized vehicle monitoring provides real-time tracking and monitoring of hazardous chemical vehicles and other vehicles prioritized for monitoring by identifying types of vehicles entering the tunnel, and provide view of monitoring videos of tunnel interior.

⑤ Risk evaluation. It is used for real-time risk evaluation of tunnel operation status, including evaluation of structural risk of the tunnel, structural risk of the adjacent tunnel, traffic risk and comprehensive operation risk.

Structural risk evaluation involves analysis of long-term monitoring data on tunnel lining crack, water leakage, spalling and water table. Its evaluation result can comprehensively reflect the current tunnel structure risk level to help tunnel operators prevent major structural incidents. Traffic risk evaluation means evaluating traffic flow in the tunnel and its surrounding road network, congestion data and vehicle types to obtain current traffic risk rating of the tunnel. Comprehensive operation risk is the final risk level obtained taking into account structural risk and traffic risk evaluation results.

5. Conclusions

① Due to its geographical location, urban tunnels are unique in terms of proximity to buildings, transportation, hydrology, vertical alignment, and social environment, and their operating risks are generally higher than general highway tunnels.

② Key issues in evaluation of operation risk for urban tunnels include complex, diversified evaluation factors, inadequate timeliness of evaluation, undiversified evaluation dimension and difficulty in determining evaluation level.

③ Research on urban tunnel operation risk evaluation shall focus on "people-vehicle-tunnel-environment-management" as a whole and take advantage of IoT and big data technology to advance real-time, intelligent and IT-based risk evaluation.

④ The proposed urban tunnel operation risk evaluation and management system based on IoT and big data analysis technology offers a new solution to real-time, intelligent and IT-based risk management for urban tunnels.
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