Research on Remote Calibration Technology and Device Innovation of Tunnel Carbon Monoxide Detectors

Lu Peng[1], Xiaofan Feng[1,*], Yu Tang[1], Xiaokun Han[1], Jinjin Cao[1], Chunguang Lan[2], Shangjun Li[3], Wenying Su[1]

[1]*Highway Research Institute of the Ministry of Transport, Beijing, China*
[2]*Beijing Construction Engineering Research Institute Co., Ltd., Beijing, China*
[3]*Tibet Transport Survey, Design and Research Institute Co., Ltd., Tibet Autonomous Region, China*
[*]*Corresponding Author*

Abstract: With the rapid expansion of tunnel infrastructure and increasingly stringent safety regulations, the calibration accuracy of carbon monoxide (CO) detectors has become a critical component of transportation safety systems. Traditional manual calibration methods face limitations in efficiency, cost, and environmental adaptability, prompting the rise of remote calibration technologies known for their non-contact, intelligent, and efficient features. This study focuses on the development of remote calibration systems for tunnel-based CO detectors and analyzes three representative technical approaches: an integrated system combining flexible gas containers and remote control mechanisms, a portable modular toolkit optimized for on-site adaptability, and a pose-sensing actuator system that restores physical calibration operations remotely. From the perspectives of structural design, workflow execution, error control, and system scalability, this paper verifies the practical feasibility and engineering adaptability of remote calibration under complex tunnel conditions. The results indicate that with integrated hardware-software systems and platform-based management, remote calibration will play an increasingly vital role in intelligent maintenance and carbon monoxide monitoring within smart transportation frameworks.

Keywords: Tunnel Safety; Carbon Monoxide Detection; Remote Calibration; Electric Actuator

1. Introduction

As a vital infrastructure in the modern transportation system, tunnels feature enclosed environments with limited air circulation. Under heavy traffic conditions, harmful gases such as carbon monoxide (CO) emitted by vehicle exhaust are prone to accumulation in tunnels, threatening the health and safety of drivers and workers [1]. Consequently, real-time monitoring and early warning systems for tunnel carbon monoxide constitute a critical component of safety assurance. As the core sensing element, the accuracy of detection data from carbon monoxide detectors serves as the foundation for the entire system's operation [2-7]. However, most existing carbon monoxide detectors are installed in the middle or top of tunnels, an area characterized by high humidity, high dust concentration, and widespread equipment distribution. Traditional calibration methods, such as dismounting for off-site calibration or manual on-site adjustment, suffer from low efficiency, high costs, poor equipment versatility, and significant construction disruption, failing to meet the operational and maintenance demands of rapidly evolving transportation infrastructure. Therefore, "remote calibration" technology—grounded in key principles such as flexible container design, remote control, and portable application—has emerged as a viable pathway to enhance the intelligent operation and maintenance capabilities of carbon monoxide detectors.

This study is centered on the remote calibration system for tunnel carbon monoxide detectors. Drawing on multiple innovative patents and research and development devices, it systematically analyzes the existing technical difficulties and engineering pain points in remote calibration. The study proposes solutions covering device configuration, implementation plans, and overall processes, with the aim of providing the industry with more adaptable and efficient practical technical solutions.

2. Research Status at Home and Abroad

As the capacity of highway networks lags far behind traffic demand, the continuous increase in motor vehicle exhaust emissions presents a substantial threat to urban air quality and public health. Research by the U.S. Environmental Protection Agency (USEPA) reveals that up to 95% of carbon monoxide (CO) in urban environments stems from motor vehicle emissions. In the domain of pollution modeling, such emissions are typically analyzed via quantitative methods based on the composite characteristics of "line sources" (e.g., road traffic flow) and "point sources" (e.g., fixed industrial facilities) [1].

Currently, European and American countries lead internationally in formulating carbon monoxide detector standards and conducting long-term calibration research. The National Institute of Standards and Technology (NIST) has developed a CO standard gas reference device using cavity ring-down spectroscopy (CRDS) technology, achieving an uncertainty of 0.1%; Germany's PTB has developed a tunnel simulation gas distribution system to reproduce CO concentration fluctuation curves for dynamic calibration; the EU "Smart Tunnel" project has integrated digital twin and machine learning to build a predictive maintenance platform, enhancing equipment operational stability. Tabarra et al. [8] used CFD software to establish a regular tunnel model to simulate jet flow, and comparative analysis of simulation results and actual measurements showed high consistency between the conclusions of this constant-temperature numerical simulation and real-world data. GW Truong et al. [9] proposed Frequency Agile Rapid Scan Spectroscopy (FARS), in which a high-bandwidth electro-optic modulator converts selected laser sidebands into continuous optical cavity modes, showing promise for fast and sensitive trace gas measurement and chemical kinetics research.

China has also achieved notable advancements in the traceability of standard gases and sensor compensation. Zhu Chun et al. [10] compared the calculation of required air volume based on China's tunnel ventilation specifications and PIARC 2004, theoretically deriving and proving that the value of the domestic vehicle density coefficient was incorrect and correcting the calculation formula for carbon monoxide required air volume. Ye Wei et al. [11] fitted a calculation formula for CO concentration limits under normal operating conditions using the Coburn-Forster-Kane equation (CFK equation) and combining with the distribution characteristics of CO concentration in different forms of transverse ventilation tunnels. Cao Ke et al. [12] designed a cavity ring-down spectroscopy measurement device based on Pound-Drever-Hall (PDH) frequency-locking technology, addressing limitations of traditional physical measurement standards. Chen et al. [13] constructed a cavity ring-down spectrometer for trace gas detection using a telecommunication distributed feedback (DFB) diode laser, featuring a simple structure, high sensitivity, and strong accuracy, which is highly suitable for quantitative analysis of trace gases.

However, the remote calibration technology for tunnel carbon monoxide detectors in China remains in its infancy, with most related systems still dependent on manual on-site operations, which are inefficient and cumbersome. Most studies focus on sensor response correction and automatic calibration algorithms, lacking systematic design of device structures and remote interaction mechanisms. In recent years, however, a research team from the Highway Research Institute of the Ministry of Transport has proposed a series of feasible technical solutions based on practical application needs: including portable calibration tools using flexible containers to create standard gas spaces, remote control mechanisms integrating electric actuators and posture sensing technologies, and a complete systematic device design with integrated overall structure and fixed processes. These designs provide an important foundation for transforming remote calibration from an experimental concept into engineering application.

3. Key Technologies and System Design

The core of designing a remote calibration system for tunnel carbon monoxide detectors involves developing a device that can adapt to complex field environments, enable remote control, and ensure high-precision gas concentration generation and calibration control. This study focuses on the analysis of three key technical systems: (1) the overall structure and execution logic of the remote calibration device; (2) the design of portable calibration modules and flexible containers; (3) remote motion-replication devices based on pose sensing and electric actuators.

3.1 Composition and Functions of the Remote Calibration Device

The remote calibration device is designed to conduct non-contact and non-dismantling standard gas calibration for carbon monoxide detectors installed on tunnel walls or ceilings via remote network control. As illustrated in Figure 1, the system primarily comprises a flexible standard container, electric actuating components, a network communication module, and a monitoring terminal system.

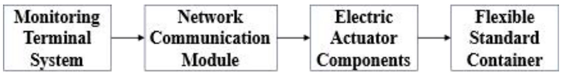

Figure 1. Framework Diagram of Remote Calibration Device for Tunnel Carbon Monoxide Detector

Among them, the flexible standard container establishes a closed and controllable gas environment for the device. It incorporates components such as a reference standard, gas mixing and exhaust systems, and elastic interfaces, which can form an airtight connection with the sensor to be calibrated. The electric actuating components include servo motors, solenoid valves, linear motors, etc., responsible for executing actions such as knob adjustment and switch control under remote commands. The network communication module establishes two-way connection via 4G network transmission, while the monitoring terminal system completes remote control and status monitoring synchronously through a display screen and control panel. The overall connection of the entire calibration device is shown in Figure 2.

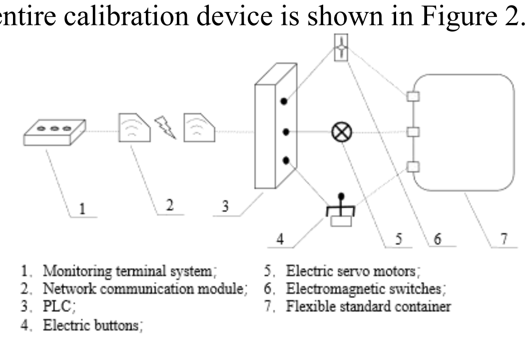

Figure 2. Overall Connection Diagram of the Remote Calibration Device

The system enables automatic mixing of CO standard gases at multiple concentrations, monitoring of gas conditions inside the flexible container, comparison of readings between the instrument under calibration and the reference standard, and execution of procedural calibration commands, demonstrating good scalability and engineering adaptability.

3.2 Flexible Container and Portable Calibration Kit Technology

In response to the confined spaces and varying sensor heights within tunnels, the research team designed a flexible standard container structure fabricated from plastic materials. Compared with traditional fixed-volume metal chambers, its primary advantages include: (1) The container shape can adapt to different installation locations, enhancing on-site adaptability; (2) A standard gas environment can be established without vacuum pumping, reducing system complexity; (3) When combined with the elastic interface and wall-mounted bracket design, it enables rapid assembly and stable airtight connections, as shown in Figure 3.

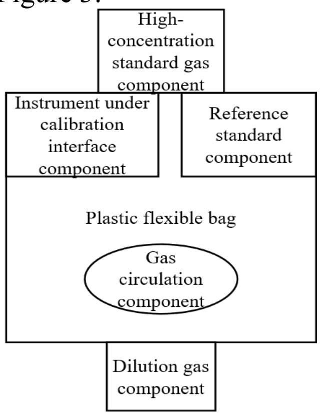

Figure 3. Schematic Diagram of the Portable Gas Sensor Calibration Kit Structure

Building on this foundation, a portable gas sensor calibration kit for more convenient on-site operations has also been developed. Utilizing a lightweight flexible plastic bag as the gas space matrix, the kit integrates a high-concentration standard gas bag, a reference standard, a dilution gas module, and an internal gas mixing device, enabling single-person operation, plug-and-play components, and rapid in-situ generation of standard-concentration gases.

Of particular note is that the gas inlet/outlet components, sensor interfaces, and reference standard connections in this kit all adopt bottle-cap threaded seals and aviation plug anti-leakage structures. This ensures both rapid on-site assembly and tight sealing while enhancing the system's versatility and measurement stability.

3.3 Automatic Calibration Module Based on Pose Sensing

To remotely perform various control actions (such as rotating, sliding, pressing, etc.), the research team further proposed a remote-control system based on pose sensing and electric actuators. The design concept is to replicate the physical behaviors of calibration operations (such as turning knobs, pressing buttons, etc.) at the monitoring end. Pose sensing elements (such as rotary encoders, linear potentiometers, toggle switches, etc.) convert these operations into voltage, current, or digital signals, which are processed by the PLC module and transmitted to the calibration site via the network. The system framework diagram of the calibration device is shown in Figure 4.

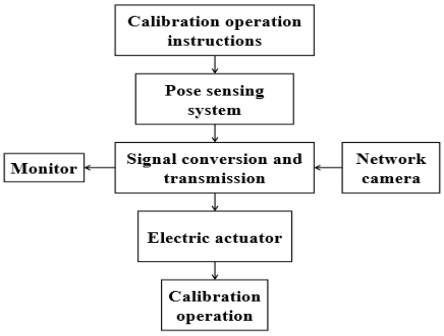

Figure 4 Framework Diagram of the Remote Calibration Device

At the calibration site, the received digital signals are then converted to analog signals that control actuators (such as servo motors, linear motors, and electromagnetic buttons) to perform corresponding physical actions, thereby replacing on-site manual calibration steps. This solution not only reduces reliance on high-cost "teleoperation" platforms but also significantly enhances the accessibility and stability of remote calibration technology.

In addition, the system supports real-time video feedback and status monitoring, enabling dynamic adjustments based on monitoring footage to ensure the precision and synchronization of operational responses. A series of standardized connection interfaces, such as servo motor-knob, linear motor-slide bar, and electromagnetic button-push button, also significantly reduce the field debugging complexity of the device.

4. Remote Calibration Method and Process Design

The core principle of remote calibration for tunnel carbon monoxide detectors lies in using flexible standard containers and electric control modules to establish a standard gas environment with high consistency, remote controllability, low interference, and high repeatability. Through data comparison between the reference standard and the device under calibration, value correction is performed. To ensure accuracy and operability, designing a clear and standardized process for calibration steps and defining the technical specifications of each link are required. The specific workflow is depicted in Figure 5.

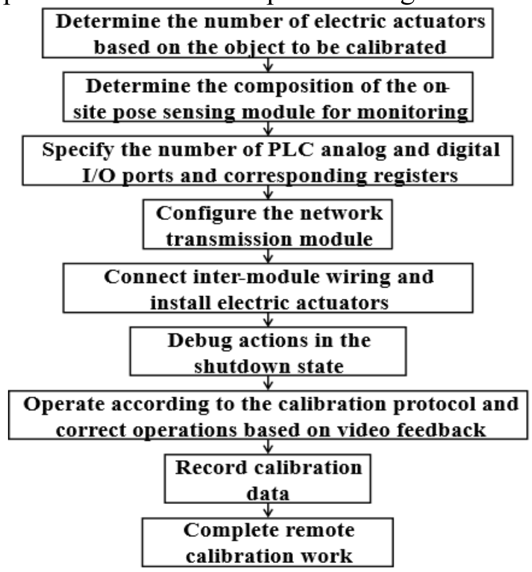

Figure 5. Remote Calibration Workflow Diagram

4.1 Decomposition of Calibration Process and Operation Steps

The primary objective of the remote calibration system is to achieve precise, non-contact calibration of carbon monoxide detectors in complex tunnel environments. The overall structure of the device proposed by the research team comprises a flexible standard container, electrical actuating components, a network communication module, and a remote monitoring system. The flexible container can adaptively deform according to the sensor's installation position and create a controllable calibration environment via means such as standard gas injection and reference standard comparison. Electrical actuating components (e.g., servo motors and solenoid valves) receive remote commands to complete actions like gas circuit switching and knob adjustment, while the remote control system enables command transmission and real-time video monitoring through wireless communication to ensure each operation is accurate and controllable. The entire system integrates functions such as automatic gas mixing, closed control, remote operation, and multi-device compatibility, featuring strong adaptability and high integration, which provides effective support for intelligent gas monitoring and maintenance in tunnel scenarios.

4.2 Calibration Accuracy Control and Uncertainty Evaluation

On this basis, the research has further developed a portable gas sensor calibration kit, which is suitable for on-site calibration needs in space-constrained and highly challenging working environments. Using a plastic flexible bag as the container, the kit is equipped with a high-concentration standard gas bag, a reference standard, a dilution pump, and a flexible mixing mechanism, enabling rapid generation and uniform distribution of standard gases under single-person operation. All components adopt screw-on cap sealing and aviation plug connections to ensure fast on-site installation and reliable airtightness. Compared with traditional bulky calibration devices, this portable kit not only significantly reduces transportation and assembly costs but also optimizes adaptability and operational efficiency, making it suitable for popularization and application in complex environments such as urban utility tunnels and tunnel sidewalls.

5. Technical Challenges and Development Trends

Although the application of remote calibration technology in tunnel carbon monoxide detectors exhibits broad prospects, it still confronts numerous key technical challenges in practical deployment and engineering practice. These challenges primarily focus on aspects such as sensor characteristics, system stability, cross-interference issues, and technology adoption. Simultaneously, with the rapid advancements in emerging technologies like artificial intelligence, quantum sensing, and the Internet of Things, remote calibration systems also possess the potential for further optimization and expansion in the future.

6. Conclusions and Recommendations

With the steady growth in the number of tunnel projects and the enhancement of safety supervision requirements, the metrological accuracy of carbon monoxide detection equipment has become a critical component in traffic safety assurance. Traditional manual calibration methods exhibit substantial limitations in efficiency, cost, and environmental adaptability, driving remote calibration technology to increasingly emerge as a key research focus in the industry.

Based on a review of relevant domestic and international research, this paper systematically summarizes and analyzes three representative technical approaches to remote calibration, covering different technical modes such as device-integrated type, portable module type, and action-reduction type. Discussions are focused on aspects such as structural configuration, operation processes, error control, and system scalability, evaluating their practical application effects and technical prospects in tunnel gas monitoring scenarios.

The study indicates that remote calibration technology is now essentially ready for engineering implementation. Future development should be directed toward the following directions: improving the standard gas reference system to enhance system robustness; promoting modular and standardized design to reduce deployment thresholds; establishing standardized industry technical specifications to enhance adaptability; and integrating with IoT platforms to develop distributed remote calibration systems for smart transportation scenarios.

Through the coordinated development of software-hardware integration, intelligent control, and platform-based management, remote calibration technology will assume a pivotal role in guaranteeing detection accuracy, improving maintenance efficiency, and reducing operation and maintenance costs, further facilitating the intelligent upgrading of China's tunnel safety system.

Acknowledgments

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