E3S Web of Conferences **573**, 02003 (2024) https://doi.org/10.1051/e3sconf/202457302003
SDER 2024

Real-Time Monitoring Technology for Carbon Emissions in Mountain Expressway Tunnel Construction

Jiaqi Yang[1], Jingdong Li[1], Zhiqiang Liu[2], Rongrong Qiang[2,*], Yongmin Liu[3], Zhijun Li[4], Hua Liang[5]

[1]Yunnan Linshuang Expressway Co., Ltd, Kunming, 650000 China
[2]Research Institute of Highway Ministry of Transport, Beijing, 100088 China
[3]Yunnan Jiaotou Group Yunling Construction Co., Ltd, Kunming, 650000 China
[4]China Nonferrous Metals Industry Sixth Metallurgical Construction Co., Ltd, Zhengzhou, 450000 China
[5]China Railway 15th Bureau Group Co., Ltd, Shanghai, 200000 China

Abstract: The complexity of tunnel construction places it in a position of great importance in the overall construction of highways, and the carbon emissions generated during its construction also account for a large portion. The report of the 20th National Congress of the Communist Party of China pointed out the need to "actively and steadily promote carbon peaking and carbon neutrality." As one of the main contributors of carbon emissions, the transportation industry needs to actively increase its efforts to reduce emissions, innovate ways to reduce emissions, and not overlook any sources of carbon emissions. This article relies on the Linshuang Expressway project , which combines theoretical calculation logic with information and Internet of Things technology to complete the construction of a real-time monitoring system for carbon emissions during tunnel construction in mountainous areas. Through this system, construction carbon emissions can be visualized and monitored in real-time, providing reliable data support for emission reduction in tunnel construction, and providing technical references for promoting low-carbon, clean, and green highway tunnel construction, in order to further support the development of a strong transportation country.

1. Introduction

With the exacerbation of global climate change and energy crises, reducing carbon emissions has become a global consensus. Controlling carbon dioxide emissions is one of the crucial measures to address climate change and greenhouse gas emissions. As the global economy develops and the population grows, carbon dioxide emissions have been increasing annually, leading to serious consequences such as rising global temperatures, exacerbating climate change, and deteriorating ecological environments. Currently, the main sources of carbon emissions include human activities and natural processes, with the largest emissions from human activities coming from the electricity, transportation, industrial, and construction sectors.

To mitigate global warming, countries and the international community have been taking effective measures to reduce carbon dioxide emissions. One of the primary measures to achieve this goal is the adoption of clean energy and energy-saving technologies, promoting economic structural transformation, and adjusting energy consumption structures. Additionally, economic and policy measures such as forest carbon sinks and carbon trading are also important measures to reduce greenhouse gas emissions. The Paris Agreement sets targets and efforts for reducing greenhouse gas emissions around 2030. China, as one of the largest greenhouse gas emitters in the world, has committed in the agreement to peak its carbon dioxide emissions around 2030 and achieve carbon neutrality by 2060.

The transportation industry is one of the largest contributors to global carbon emissions, with carbon emissions from tunnel construction sites being particularly prominent. During tunnel construction, the operation of excavators, mixers, and other equipment generates a large amount of carbon dioxide emissions. Moreover, due to the narrow construction environment and poor ventilation conditions in tunnels, effective carbon emission control is difficult to achieve[1].

In recent years, Cyber-Physical Systems (CPS) technology, as a new type of system integration technology, has been successfully applied in various fields such as industry, transportation, agriculture, and healthcare. The core idea of CPS is to integrate information technology with physical technology to achieve real-time monitoring, control, and adaptive management of the physical world0. Furthermore, due to the unique environment of tunnel construction, traditional monitoring methods face many difficulties. Developing a real-time carbon emission monitoring system for tunnel construction sites based on CPS technology will help address these issues[2-4].

There have been many research results on monitoring systems, but most of them focus on the hardware level, lacking comprehensive research on monitoring systems.

---

[*] Corresponding author: rr.qiang@rioh.cn

Moreover, most monitoring systems cannot achieve real-time monitoring, but CPS technology can better solve these problems. By combining the physical world with information technology, CPS technology enables real-time monitoring of construction sites and real-time processing and analysis of monitoring data, which can better grasp the status of carbon emissions at construction sites and take corresponding measures for control. Therefore, the development of a real-time carbon emission monitoring system for tunnel construction sites is not only conducive to the implementation of national environmental protection policies and international agreements on greenhouse gas emissions reduction but also of great significance for improving the quality of construction environments, reducing environmental pollution, and protecting the health of workers.

The purpose of this paper is to develop a real-time carbon emission monitoring system for tunnel construction sites based on CPS technology, achieving real-time monitoring of carbon emissions at tunnel construction sites. The system consists of two parts: the physical layer and the virtual layer. The physical layer monitors carbon emissions at construction sites by deploying environmental sensors, while the virtual layer includes a computing layer and an interaction layer. In the computing layer, servers and databases are used for data processing and storage, while the interaction layer provides visual monitoring interfaces and data analysis interfaces. Such a system not only enables real-time monitoring but also provides accurate data support. Based on this, real-time control of carbon emissions can be achieved through the design of feedback mechanisms[5-7].

2. Carbon Emission Calculation Logic

2.1. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a systematic evaluation method aimed at assessing the environmental and social impacts of products, services, technologies, or systems throughout their life cycle. It typically includes the impacts from raw material extraction to processes such as manufacturing, usage, disposal, and handling, comprehensively assessed based on environmental impact categories (e.g., greenhouse gas emissions, energy consumption, waste generation). The purpose of LCA is to provide decision support for environmental and socially sustainable development and, to some extent, address environmental issues and impacts throughout the life cycle.

In the context of tunnel construction carbon emission calculations, LCA can prove effective. This approach will be utilized to assess the overall environmental impact of tunnel construction, encompassing the production and transportation of tunnel materials, energy usage, and carbon emissions during construction, as well as carbon emissions during the use and demolition of the tunnel.

2.2. Calculation Boundary of Carbon Emissions

The types of carbon emissions during tunnel construction can be divided into explicit carbon emissions and implicit carbon emissions based on whether they directly generate carbon emissions. Explicit carbon emissions constitute the vast majority, and their sources are divided into construction areas, office and living areas, with the carbon emissions from office and living areas no longer considered (as there is already considerable research on carbon emissions directly generated by human activities, which this paper will not further consider). The carbon emissions in the construction area mainly come from construction machinery. For convenience in calculation, tunnel construction machinery is classified into three categories based on the degree of carbon emissions: excavation machinery, transportation machinery, and other auxiliary machinery. Excavation machinery mainly includes tunnel boring machines, bulldozers, etc. Transportation machinery includes tunnel boring transport vehicles, grouting pump vehicles, support material transport vehicles, etc. Other auxiliary machinery includes cranes, mixers, support frames, support machines, etc.

When determining the calculation list, considering various factors such as system development time and construction environment, only the most representative machinery is considered. Among them, only tunnel boring machines are considered for excavation machinery, various types of transport vehicles are considered for transportation machinery, and only cranes are considered for other auxiliary machinery. Tunnel boring machines are the most important mechanical equipment for tunnel construction excavation and are typical fuel-consuming equipment, accounting for a large proportion of carbon emissions on construction sites. Various types of transport vehicles are typical representatives of large-scale mobile carbon emission sources on site, with the vast majority of on-site transport vehicles being fuel-consuming. Electrically consuming transport vehicles such as new energy heavy-duty trucks are not considered for the time being. Different vehicle types have their corresponding diesel consumption rates, which need to be calculated separately. Cranes are non-mobile vertical transportation carbon emission sources, widely scattered on construction sites, and are typical electrically consuming equipment with large carbon emissions on construction sites.

2.3. Calculation Model of Carbon Emissions

The calculation model will be applied in the CPS carbon emission real-time monitoring and visualization system to monitor the carbon emissions of the three typical types of construction machinery mentioned above.

$$C_{\mathrm{Total}} = C_x + C_y + C_z \tag{1}$$

In the formulas, C_{Total} represents the total carbon emissions monitored by the system at the construction site, C_x represents the carbon emissions generated by excavation machinery, C_y represents the carbon emissions generated by transportation machinery, and C_z represents the carbon emissions generated by other auxiliary machinery.

2.3.1. Excavation Machinery

Tunnel boring machines belong to fuel-consuming equipment, assuming each tunnel boring machine has its own fuel consumption rate.

$$C_x=\sum_{i=1}^{m}\left(\frac{t_i}{3600}\right)\times V_i\times f_o \tag{2}$$

In the formula, m is the number of tunnel boring machines; i represents the i-th tunnel boring machine; ti is the operating time of the i-th equipment, measured in s; Vi is the fuel consumption rate of the i-th tunnel boring machine, measured in kg/h; fo is the carbon emission factor of the fuel. Where m and ti can be directly obtained from the CPS monitoring system, Vi and fo can be obtained from relevant data.

2.3.2. Transportation Machinery

The carbon emission calculation of on-site transportation machinery is essentially equivalent to the calculation logic of vehicle operation carbon emissions, only considering fuel-consuming transport vehicles.

$$C_y=\sum_{i=1}^{n}\left(\frac{t_i}{3600}\right)\times V_i'\times f_o' \tag{3}$$

In the formula, n is the number of on-site transport vehicles; i represents the i-th transport vehicle; ti' is the operating time of the i-th transport vehicle, measured in s; Vi' is the fuel consumption rate of the i-th transport vehicle, measured in kg/h; fo' is the carbon emission factor of gasoline or diesel. Where n and ti can be directly obtained from the CPS monitoring system, Vi' and fo' can be obtained from relevant data.

2.3.3. Other Auxiliary Machinery

Cranes are electrically consuming equipment, and different equipment have different rated power.

$$C_z=\sum_{i=1}^{k}\left(\frac{t_i}{3600}\right)\times P_i\times f_e \tag{4}$$

In the formula, k is the number of cranes currently in use; i represents the i-th crane; ti is the operating time of the i-th crane, measured in s; Pi is the rated power of the i-th crane, measured in kW; fe is the carbon emission factor of electricity. Where k and ti can be directly obtained from the CPS monitoring system, Pi and fe can be obtained from relevant data.

2.4. Carbon Emission Factors

Greenhouse gases mainly include carbon dioxide (CO_2), methane (CH_4), and various other gases, which contribute to the greenhouse effect, with CO_2 being the most significant contributor. Therefore, greenhouse gas emissions are commonly referred to as carbon emissions. During tunnel construction, greenhouse gas emissions are primarily caused by energy consumption processes, mainly from the combustion of fossil fuels. Consumption of electricity and natural gas also contributes to carbon emissions. In studies, carbon emissions are quantified only in terms of CO_2 emissions. Other gases can be converted to CO_2 equivalents using the Global Warming Potential (GWP) to standardize measurement. Additionally, the energy efficiency ratio is set to 100% for ease of quantification.

To quantify the CO_2 emissions produced by various activities, carbon emission factors are introduced, representing the coefficient of CO_2 produced per unit activity. Recommended values for fuel-type carbon emission factors is shown in Table 1. According to the 2019 Baseline Emission Factors for Emission Reduction Projects in the China Regional Power Grids, the carbon emission factor for electricity in the Guangxi region is 0.8042kgCO_2/kWh. Due to differences in economic levels, production systems, and other factors among regions, carbon emission factors vary significantly. After comprehensive consideration, the recommended values for fuel-type carbon emission factors are as shown in the table below.

Table 1. Recommended values for fuel-type carbon emission factors.

Type	Carbon Emission Factors kg CO_2eq/kg
Diesel	1.921
Gasoline	2.171

3. Construction of Carbon Emission Monitoring System

3.1. Cyber-Physical System

A Cyber-Physical System (CPS) is a type of system technology that integrates computer science, electronics, control theory, and physics. It combines network technology, sensor technology, control technology, and computer technology to merge the virtual and physical realms. At the technical level, CPS achieves the detection, control, and optimization of real-world physical processes. CPS finds extensive applications in various fields, including intelligent transportation systems, smart grids, smart factories, smart buildings, and carbon emission monitoring systems[8-11].

A complete CPS typically consists of four interconnected parts: "Sensing, Connecting, Computing, and Control." These parts collaborate to achieve the system's goals. The diagram of CPS system is shown in Fig. 1.

Sensing: Involves collecting information and data through various sensors like temperature sensors, humidity sensors, light sensors, etc. Connecting: Involves transmitting the collected data through networks. Computing: Involves processing and analyzing the collected data at a computing center, identifying real-world behaviors, and digitizing them through modeling. Control: Involves taking appropriate control actions based on the results of data analysis.

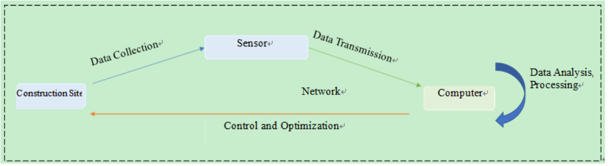

Fig.1. The diagram of CPS system

3.2. Carbon Emission Monitoring System Architecture

$$T_s\,(l,t) = T_g\,(l,t) \tag{5}$$

$$T_s\,(l,t) = T_g\,(l,t)\; T_b\,(x \qquad\quad , t) = 0 \tag{6}$$

The architecture of CPS typically comprises the physical layer, the computing layer, and the interaction layer. The physical layer refers to tangible devices such as sensors and actuators that exist in the real world. They monitor and control the physical environment, transmitting data to the computing layer for processing. The computing layer serves as the core of the CPS system. It employs computer systems to store, process, analyze, and control data, acting as a bridge between the physical and interaction layers. The interaction layer acts as the interface between the system and users. Through human-machine interfaces, mobile devices, and other means, users can monitor and control the system. These three layers are interconnected and require coordination to ensure the stability and security of system operation.

A carbon emission monitoring system at a tunnel construction site, built on CPS technology, similarly encompasses these three dimensions[12-14].

3.2.1. Physical Layer

The physical layer, also known as the hardware system, comprises sensors as its vital components. These sensors are responsible for collecting information from the physical world and converting it into electrical signals for transmission to the computing layer.

In a carbon emission monitoring system at a tunnel construction site, appropriate environmental sensors need to be installed. Greenhouse gases are particularly sensitive to changes in temperature and humidity, necessitating the installation of sensors such as carbon dioxide sensors, air quality sensors, temperature sensors, and humidity sensors. These sensors can collect various environmental data from the site and transmit it for processing.

Among these sensors, the carbon dioxide sensor plays a primary role. It is designed to detect the concentration of carbon dioxide, directly providing the numerical values of carbon emissions at the tunnel construction site. Generally, a carbon dioxide sensor consists of three main parts: the display module, the sensing element, and the circuit control module. The display module includes data output interfaces, data storage, protective covers, etc., primarily converting electrical signals into visible signals. The sensing element typically comprises carbon dioxide absorbers and electrodes. The carbon dioxide absorber can change resistance according to the concentration of carbon dioxide, thereby altering the electromotive force of the electrodes. This change is detected through the circuit section. The circuit control module mainly consists of amplification circuits, signal conversion circuits, and control circuits. The amplification circuit amplifies the tiny signals from the sensing elements for detection by the circuit. The signal conversion circuit converts the electrical signals into digital signals for data processing, while the control circuit manages the operation status of the sensor.

There are various types of carbon dioxide sensors, including electrochemical sensors, optical sensors, and sensors based on micro-nano materials. It's crucial to select carbon dioxide sensors with high sensitivity, low noise, short response time, high stability, and low cost.

In addition to carbon dioxide sensors, environmental sensors like temperature and humidity sensors are also necessary. Temperature and humidity can affect the absorption of carbon dioxide, so knowing the environmental conditions is essential for adjusting concentration values. Temperature sensors, as electrical sensors, are used to measure on-site temperature. Different types of temperature sensors have variations in the technology and materials used in their sensing elements. Commonly used temperature sensors include thermocouples and thermistor-based sensors, while thermopiles and thermal capacitors are less common. Thermocouple-type temperature sensors measure temperature using two electrodes made of different metals. The electromotive force difference between the two metals changes with temperature, allowing temperature measurement. Thermistor-type sensors measure temperature through changes in resistance. The resistance varies with temperature, and the temperature is measured by monitoring the change in resistance.

To meet the requirements of the construction site and achieve multifunctionality, noise sensors, air quality sensors, and other sensors can be added. These additional sensors help in checking whether the tunnel environment meets safety standards.

Considering the need for multiple sensors to gather information, designing integrated sensors with various modules inside a control box is beneficial. This control box can include modules for carbon dioxide sensors, thermistor sensors, power supply, motherboard circuits, etc., and can be operated with multiple buttons. Externally, a fixed device made of carbon fiber boards can be used to secure the control box. This ensures installation on construction machinery and provides a dual function of protecting the internal sensors and isolating external interference.

3.2.2. Computing Layer

The computing layer consists of servers, networks, and databases. Servers are the core of the software computing layer, handling the analysis, computation, modeling, and transmission of captured data. Communication networks serve as the medium for information transfer. Given the complex conditions at tunnel construction sites and the vast amount of generated data, the network communication system needs to possess good stability, fast transmission, and high throughput.

Databases primarily store and manage data uniformly, including data input, database creation, storage, querying, and security management. Considering the complexity and specificity of data generated during tunnel construction, establishing a unified storage and management system for tunnel carbon emissions data is necessary. Factors such as response speed and reliability lead to the choice of My SQL database.

3.2.3. Interaction Layer

The interaction layer serves as the channel for interaction between personnel and the system. Its role includes allowing personnel to input or import carbon emission-related information such as tunnel names, equipment categories, models, and power, and visualizing carbon emission data for easy understanding of the emission situation at the construction site.

A carbon emission monitoring software system was developed specifically for the construction site of the Linshuang Expressway Tunnel. The visualization monitoring interface, as shown in the diagram, displays detailed information about each tunnel. It includes the operating status of monitored equipment during the construction period, cumulative operating time, carbon emission levels, and provides warnings for exceeding emission standards. The interface also presents the results of data analysis using various two-dimensional charts (such as line graphs and histograms) to display real-time and cumulative carbon emissions on-site. Through this interface, personnel can intuitively and comprehensively understand the carbon emission situation at the construction site.

4. Conclusion

To delve into the carbon emissions from mountain tunnel construction, and achieve real-time monitoring and data visualization, this study relies on the Linshuang Expressway project to investigate the atmospheric carbon emissions during its construction phase.

Firstly, the foundational logic for monitoring carbon emissions data was established using the Life Cycle Assessment (LCA) method. After fully considering the carbon emissions generated from material production and transportation during the construction phase, the carbon emissions from the energy consumption of construction machinery will be verified and supplemented by the monitoring system. Considering the conditions at the construction site, the boundaries of carbon emissions were defined in the calculation list. The monitoring system's targets were divided into three typical types of machinery: excavation machinery, transportation machinery, and other auxiliary machinery, which are representative of the entire construction site.

Secondly, a computational model for the monitoring system based on Cyber-Physical Systems (CPS) was established, combining the LCA analysis. Based on the types of energy consumption and the operation modes of machinery, the carbon emission calculation methods for the three types of machinery were determined. By collecting and organizing on-site construction data of mountain expressway tunnel construction and analyzing it with mature databases from abroad, carbon emission factors were then specified.

Lastly, based on CPS technology, a comprehensive carbon emission monitoring system integrating computation, networking, and the physical environment was established. Leveraging wireless sensing and IoT technologies, devices such as carbon dioxide sensors and temperature-humidity sensors were seamlessly integrated, enabling real-time collection of carbon emission data with high reliability and efficiency. Subsequently, utilizing JAVA and MySQL, a visual software was designed to compute, process, and store the collected carbon emission data, presenting the processed results in a visual format.

This paper systematically explores the integration of LCA theory with CPS to develop a monitoring system for carbon emissions in tunnel construction. It realizes real-time monitoring of carbon dioxide emissions on construction sites, providing data support for emission reduction in the transportation industry, especially in the context of the "carbon peaking and carbon neutrality" framework. This contributes to cost reduction and efficiency improvement in highway tunnel construction, propelling the rapid development of high-grade highways in China towards a format optimized for energy structure. In future research, attention can be directed towards achieving autonomous management and control of construction equipment based on the results obtained from the carbon emission monitoring system. This could involve implementing AI feedback mechanisms to achieve unmanned operations and automatic control of the carbon emission behavior of construction site machinery.

References

1. WANG Wei-xian, WU Ling-sheng, YANG Dong-yuan. Calculation and Analysis of CO2 Emission from Expressway Construction [J] . Journal of Highway and Transportation Research and Development, 2014, 31 (02) : 150-158
2. YANG Fei, WANG Jia-xin, TIAN Hong, et al. Key Issues and Countermeasures in Building a Carbon Emission Monitoring System for Highway Transportation Network in China [J] . Transport Research, 2022, 8 (03) : 103-110
3. SHUAI Dan-dan. Energy big data and carbon emission monitoring [J] . Enterprise Management, 2021, No. 484 (12) : 104-105
4. LIU Chao, LIU Gang, XU Chong-bang, et al. Study on Service Performance Evaluation Method for Tunnel Based on Fuzzy Theory [J] . Journal of Highway and Transportation Research and Development, 2022, 39 (08) : 142-150+165
5. ZHANG Qin, ZHANG Da, ZHANG Xi-liang. Application of Online Monitoring to China's Carbon Emission Trading System: Key Issues and Policy Recommendations [J] . Journal of Environmental Economics, 2021, 6 (03) : 136-146

6. MA Hong. Research and Application of Smart Energy and Carbon Emission Monitoring and Management Cloud Platform System [J] . Computer Measurement & Control, 2020, 28 (04) : 28-31+115
7. UN Jian, ZHANG Ying, XUE Rui, et al. Formation Mechanism of Urban Traffic Carbon Emissions Based on Mobile Monitoring: Case Study of Shanghai [J] . China Journal of Highway and Transport, 2017, 30 (05) : 122-131
8. HAN Yin-ning, YUAN Yong-bo. A CO2 emission calculation model for buildings based on energy theory [J] . Journal of Engineering Management, 2014, 28 (2) : 6-10
9. Zhan J, Liu W, Wu F, et al. Life cycle energy consumption and greenhouse gas emissions of urban residential buildings in Guangzhou city [J] . Journal of Cleaner Production, 2018, 194: 318-326
10. LI Jing, LIU Yan. The carbon emission accounting model based on building lifecycle [J] . Journal of Engineering Management, 2015, 29 (4) : 12-16
11. Stephan A, Stephan L. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings [J] . Applied Energy, 2016, 161: 445-464
12. LIU Chao, LIU Gang, XU Chong-bang, et al. Study on Service Performance Evaluation Method for Tunnel Based on Fuzzy Theory [J] . Journal of Highway and Transportation Research and Development, 2022, 39 (08) : 142-150+165
13. ZHU Chang-zheng. Study on influencing Factors of Carbon Emission in Transport Industry Based on Cointegration Analysis. [J] . Journal of Highway and Transportation Research and Development, 2015, 32 (01) : 153-158
14. Xu J F, Guo C, Chen X F, et al. Emission transition of greenhouse gases with the surrounding rock weakened: a case study of tunnel construction [J] . Journal of Cleaner Production, 2019 (209) : 169