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# LIFE-CYCLE CARBON FOOTPRINT OF UNDERGROUND INFRASTRUCTURE

**Luyuan Long**[1], **Wout Broere**[1*], **Xuehui Zhang**[1,2]

**Abstract:** The construction industry is a major source of greenhouse emissions, and underground infrastructure, including tunnels, is responsible for a significant proportion of the overall carbon emissions. Studies on the carbon footprint of tunnels often focus on only part of the full life cycle or on a particular type of tunnels only, and do not consider and compare the carbon emissions of different types of tunnels over the full life cycle. This paper compares the carbon footprint of the four common types of tunnels, namely, shield tunnels, new Austrian tunnelling method (NATM) tunnels, cut-and-cover tunnels, and immersed tunnels, during the design, construction, operation and maintenance (O&M), as well as dismantling phases. A case study of a real-world tunnel project is used to quantify carbon emissions and reveal differences in emission magnitude and distribution across tunnel types and life cycle stages. Finally, this paper suggests several key carbon reduction measures for achieving a low-carbon design.

**Keywords:** Carbon footprint, Life cycle assessment, Tunnels, Low-carbon design

## 1. INTRODUCTION

In recent years, civil infrastructure has experienced rapid growth driven by economic development and urbanization. However, the construction industry has simultaneously emerged as one of the largest contributors to greenhouse gas (GHG) emissions, ranking third among industrial sectors in the United States (EPA, 2009) and accounting for approximately one-third of global carbon emissions (UNEP, 2009; UNEP, 2018; Gan et al., 2019). Among various GHGs, carbon dioxide ($CO_2$) is the most prevalent emission resulting from human activities.

Tunnels are a common form of civil infrastructure and have seen rapid development in recent years due to their ability to traverse complex terrain and reduce land use on the surface. However, tunnels account for substantial $CO_2$ emissions throughout their entire life cycle, including construction, operation, maintenance, and dismantling. Moreover, studies have shown that tunnels are among the most carbon-intensive constructions compared to other types of infrastructure. For instance, Chang and Kendall (2011) reported that although tunnels and elevated structures together accounted for only 15% of the total length of a high-speed rail project, they were responsible for as much as 60% of the $CO_2$ emissions. Similarly, in a carbon emission assessment of a mountainous highway project in China, Fei et al. (2017) found that on a per-kilometer basis for a four-lane section, tunnels and bridges exhibited the highest energy intensities, contributing 49.83% and 37.57% of total emissions, respectively, while roadbed and pavement works accounted for only 12.60%. These findings highlight the need to conduct carbon emission assessments for high-emission-density infrastructure such as tunnels in the context of global carbon neutrality.

Life cycle carbon emission analysis of tunnels typically focuses on quantifying the distribution and sources of carbon emissions across four main phases: design, construction, operation and maintenance, and dismantling. These insights form the foundation for developing targeted mitigation strategies. The design phase primarily involves planning and technical decision-making. Although this stage generates relatively low emissions directly, the choices made, such as material selection and construction methods, have a profound influence on

[1] Geo-Engineering Section, Department of Geoscience and Engineering, Delft University of Technology, Delft, the Netherlands.
Corresponding author: Dr. Wout Broere, w.broere@tudelft.nl
[2] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

emissions in subsequent phases. The construction phase tends to dominate the life cycle emissions profile, largely due to the energy-intensive production of key materials such as cement and steel. The operation and maintenance phase also contributes significantly, with emissions arising from material and energy consumption related to maintenance activities, ventilation, and lighting. In contrast, the dismantling phase is less frequently encountered in practice, as tunnels are typically designed for long service lives. Nonetheless, should this phase be required, it is expected to incur substantial carbon costs due to heavy material and equipment demands.

This study aims to examine carbon emissions associated with underground infrastructure, with a particular focus on various types of tunnels. Upon completion of the emission calculations, practical mitigation strategies should be proposed to support the transition toward low-carbon tunnel development in future projects.

This paper is organized into four main sections. The first section is the introduction. The second section is related to current practical and widely adopted methodologies for calculating tunnel-related carbon emissions. The third section is a case study showing the carbon emission distribution of various types of tunnels. Finally, the fourth section draws on the strategies for low-carbon tunnels.

## 2. EXISTING METHODS FOR CARBON EMISSION CALCULATION

Three commonly used methods for carbon emission calculation include the emission factor method, the input–output method, and the inventory analysis method.

The emission factor method calculates carbon emissions based on the average amount of greenhouse gases emitted per unit of product under normal technological, economic, and management conditions. This method is widely accepted and recommended by the Intergovernmental Panel on Climate Change (IPCC) as a standardized approach for carbon accounting. It follows the equation:

$$Emissions = Activity\ Data \times Emission\ Factor \tag{1}$$

The input–output method relies on input–output matrices to capture inter-dependencies within the economy. It enables the conversion of monetary values in sectors such as construction into corresponding energy consumption and carbon emissions. This approach is especially suitable for macro-level assessments in commercial and industrial applications.

The inventory analysis method involves breaking down the system into individual processes and summing the emissions across all stages. It also employs the same basic formula but focuses on process-level detail. This makes it more appropriate for micro-level carbon assessments.

In the field of civil engineering, the emission factor method is currently the most widely adopted. However, when applied to different life cycle stages, the calculation scenarios and data requirements may vary. The following sections provide a detailed discussion of these stage-specific approaches. The proposed framework in this paper is illustrated in Figure 1.

### 2.1. Design phase

The design phase mainly involves desktop-based activities, with electricity use for office operations being the main source of emissions. These emissions are typically negligible compared to those from other phases and are often excluded from life cycle assessments (LCA). However, it is important to recognize the far-reaching influence of design decisions on total life cycle carbon emissions. While the direct emissions from this phase are minimal, the choices such as construction mateirals and tunnel dimension can significantly shape the emissions profile of subsequent stages. Material parameters relevant to carbon emission are often associated with cement, concrete, and steel consumption. Design of dimensions may include tunnel cross-sectional dimensions, tunnel length, and reinforcement ratio. In summary, while the design phase is often excluded from direct LCA calculations due to its minimal emissions, its decisions substantially influence the overall life cycle carbon footprint of a tunnel and therefore need careful attention.

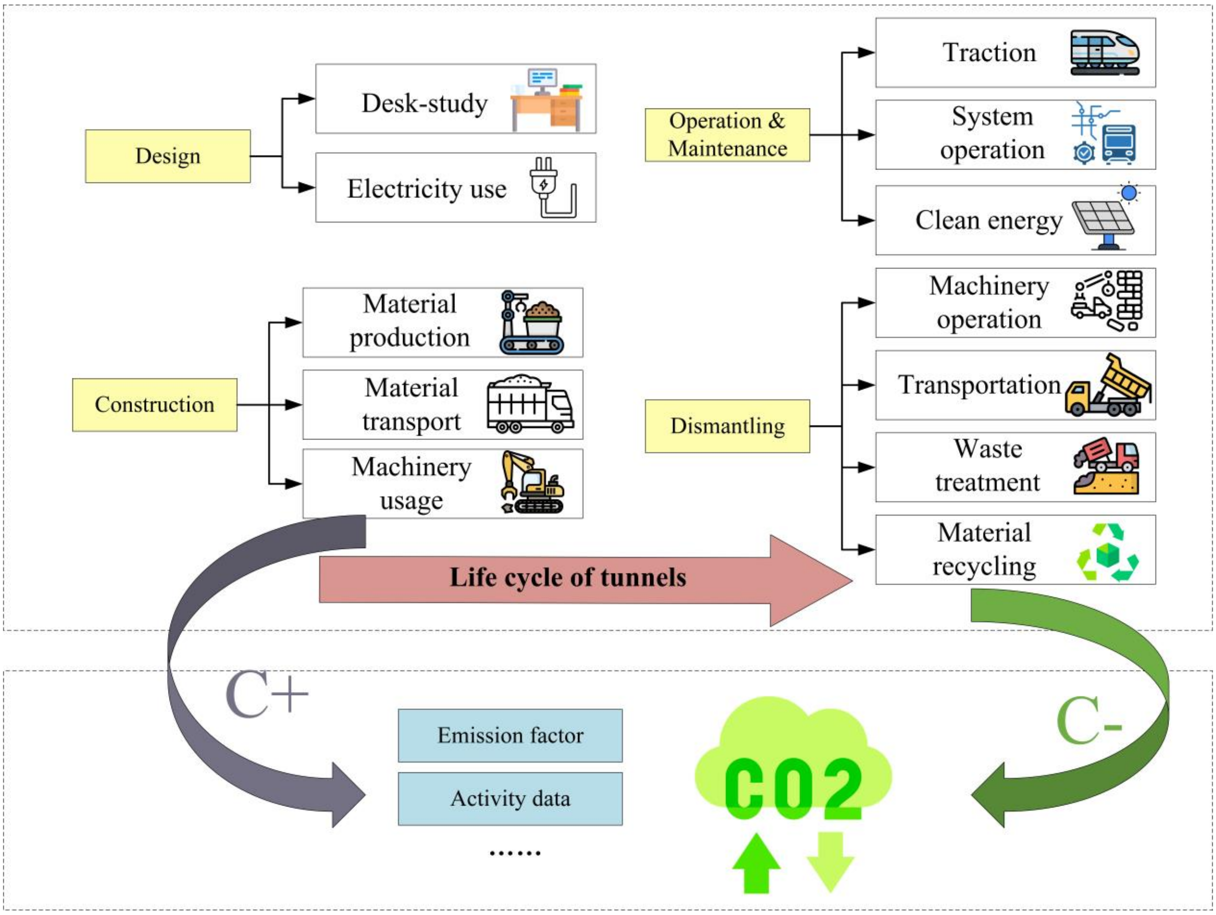


***Figure 1.*** *The life cycle of carbon emission assessment of tunnels*

## 2.2. Construction phase

Carbon emissions from material production during the construction phase are determined by accounting for both primary and recycled material inputs. These emissions depend on the material quantities, their respective emission factors, and the associated recycling rates, as expressed in the following equation:

$$C_p = \sum_i \left( M_{p,i} \times (1 - R_i) \times EF_{p,i} + M_{p,i} \times R_i \times EF_{r,i} \right) \qquad (2)$$

where: $C_p$ denotes the carbon emissions from materials production (tCO2), $M_{p,i}$ represent the consumption of each type of material (t), $R_i$ is the recycling rate for each type of material, $EF_{p,i}$ and $EF_{r,i}$ refer to the carbon emission factors of primary material and recycled material, respectively $(tCO\,2/t)$.

Total carbon emissions from material transportation are estimated based on the quantity of materials transported, the type and amount of energy or fuel consumed, the transport distance, and the corresponding emission factors, as represented in the following equation:

$$C_t = \sum_i \left( E_{t,i} \times F_{t,i} \times D_{t,i} \times EF_{t,i} \right) \qquad (3)$$

where: $C_t$ represents the carbon emissions related to transporting (kgCO2), $E_{t,i}$ is the quantity of material $i$ transported (kg), $F_{t,i}$ is the fuel or energy consumption per ton per kilometer for transporting material $i(kg/t \cdot km)$, $D_{t,i}$ is the transport distance$(km)$. $EF_{t,i}$ is the carbon emission factor for the fuel or energy used by the transport equipment $(tCO\,2/t)$.

Total carbon emissions caused from construction energy use are calculated by multiplying the amount of energy consumed by the corresponding carbon emission factor for the type of energy used by construction machinery, as expressed in the following equation:

$$C_m = \sum_i \left( E_{m,i} \times EF_{m,i} \right) \qquad (4)$$

where: $C_m$ is the carbon emissions energy consumption of machinery, $E_{m,i}$ is the total energy consumption for each type of construction machinery, determined based on actual consumption, $EF_{m,i}$ is the carbon emission factor for the energy used by each type of construction machinery.

### 2.3. Operation and maintenance phase

This study includes the energy consumption from train traction as part of the operational phase carbon emissions. In addition, energy use by lighting and ventilation systems constitutes two other major contributors that significantly affect operational emissions. Taken together, the total carbon emissions during the operation phase can be expressed by the following equation:

$$C_{\text{op}} = \left(E_{\text{traction}} + E_{\text{systems}} - S_{\text{clean}}\right) \cdot T_{\text{life}} + E_{\text{maint}} \tag{5}$$

where: $C_{op}$ represents the total carbon emissions during the operation and maintenance phase ($kgCO_2e$); $E_{\text{traction}}$ denotes the annual emissions from traction energy consumption ($kgCO_2e$/year); $E_{\text{systems}}$ corresponds to the annual emissions from tunnel system operations, including lighting and ventilation ($kgCO_2e$/year); $S_{\text{clean}}$ represents the annual carbon offset from clean energy technologies in auxiliary systems ($kgCO_2e$/year); $T_{\text{life}}$ denotes the operational lifespan of the tunnel (years); and $E_{\text{maint}}$ represents the cumulative emissions from maintenance activities ($kgCO_2e$).

### 2.4. Dismantling phase

Tunnels are often classified as control structures and, upon reaching the end of their service life, are typically decommissioned in place rather than dismantled. However, full-scale dismantling may still occur, particularly in the context of infrastructure expansion. For example, the Huangmeishan Tunnel in China was dismantled in 2022 to facilitate the upgrade of a four-lane dual carriageway to an eight-lane configuration. During the operational phase, partial dismantling may also be required when severe localized deterioration arises. In such cases, segments of the tunnel lining and support structure must be removed and subsequently reinforced or re-cast to restore structural integrity.

Current research on tunnel dismantling remains limited. However, the carbon emissions associated with this phase can be estimated using calculation methods developed for the dismantling of buildings. A representative example is the model proposed by Xiao (2021), which provides a basis for adapting emission estimates in the context of tunnels.

$$E_{end} = Q_c + Q_t + Q_h + Q_m \tag{6}$$

where: $Q_c$ represents carbon emissions from dismantling machinery operations; $Q_t$ denotes carbon emissions from the transportation of construction waste; $Q_h$ indicates carbon emissions from waste treatment activities, including landfill and incineration; $Q_m$ represents carbon emissions generated during the recovery of recyclable materials.

## 3. CASE STUDY

### 3.1. Engineering background

Dalian is a key regional economic center in China. With accelerating urbanization and ongoing industrial restructuring, the city has been expanding steadily northward.. However, north-south traffic connections remain insufficient. Severe and persistent congestion during peak hours continues to hinder mobility, posing a critical constraint on the development of adjacent urban clusters. To address this challenge, the 5.1-kilometer Dalian Bay undersea tunnel project was initiated. The tunnel will directly link the city's northern and southern districts, greatly enhancing overall accessibility and optimizing the regional transportation network.

Three alternative schemes were considered for the undersea tunnel crossing: an immersed tunnel, a drill-and-blast tunnel, and a shield tunnel. The immersed tunnel design comprises a 3,600 m immersed section, a 1,294 m buried section, and a 286 m open-cut section, yielding a total length of 5,430 m. Its structural cross-section is illustrated in Figure 2(A). The drill-and-blast tunnel extends approximately 9,214 m with cross-section shown in Figure 2(B). The shield tunnel alternative has a total length of approximately 4,765 m, comprising a 2,630 m shield-driven segment, a 1,755 m buried section, and a 380 m open-cut section. Its typical cross-section is depicted in Figure 2(C).

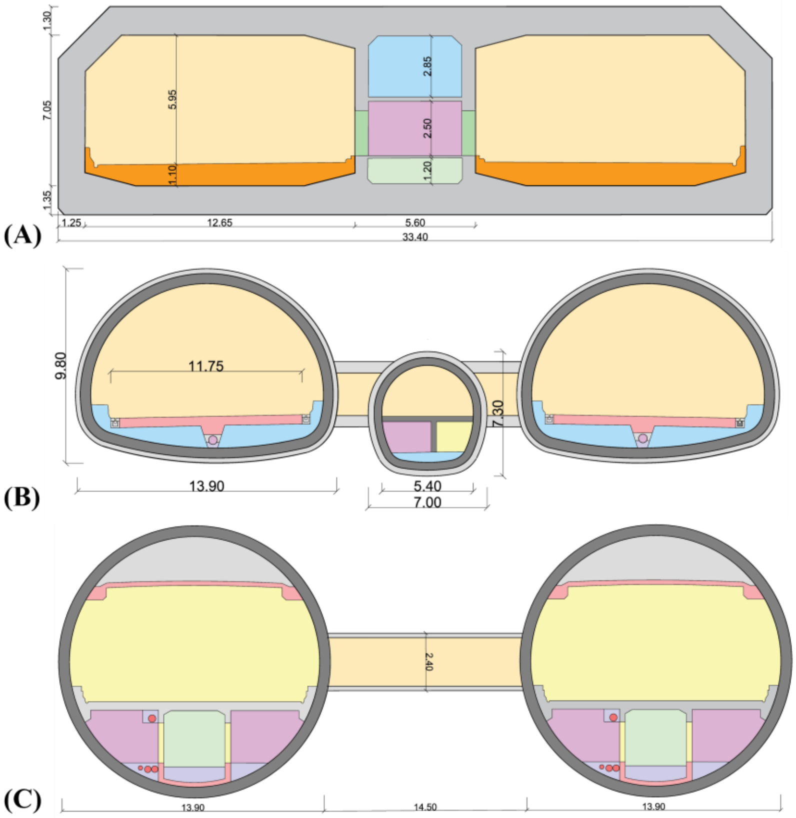


***Figure 2.*** *Cross-sections of three types of tunnel: (A) Immersed tunnel; (B) Drill-and-blast tunnel; (C) Shield tunnel.*

### 3.2. Carbon emission calculation of the construction phase

This study first focuses on carbon emissions during the tunnel construction phase for the three proposed tunnel schemes. The calculations account for the design lengths, cross-sections (considering main tunnel, connection passages, and cross-passages), and steel reinforcement distribution for each tunnel. Since this engineering case is based on detailed project conceptual design documents, material transportation $C_t$ and machinery energy consumption $C_m$ are temporarily excluded from consideration. The carbon emissions taken for the calculation in this case are from the regional database, shown in Table 1.

***Table 1.*** *Primary carbon emission factors used in this case study*

| Material type | Carbon emission factor | Factor unit | Source |
|---|---|---|---|
| Concrete | 385 | Kg CO2/m³ | Ministry of Housing and Urban-Rural Development of the People's Republic of China, (2019) |
| Steel | 2340 | Kg CO2/t | |
| Electricity | 0.5876 | Kg CO2/ kWh | National Power $CO_2$ Emission Factors, (2021) |

The emission calculation process takes into account different sections of the tunnel. For instance, the immersed tunnel in this project is divided into immersed, buried, and open sections, each corresponding to distinct cross-sectional functionalities, resulting in varying cross-sectional areas. The primary quantities for the three types of tunnels are summarized in Table 2.

***Table 2.*** *Amount of major material use in three types of tunnel*

| Tunnel type | Concrete (m³) | Steel(t) |
|---|---|---|
| Immersed tunnel | 681917.14 | 26765.25 |
| Drill-and-blast tunnel | 534270.86 | 20970.13 |
| Shield tunnel | 249953.24 | 9810.66 |

The final results include the total carbon emissions generated during construction for each scheme, as well as the unit carbon emissions per unit length for each cross-section. The key design parameters and carbon emission calculations for the three tunnels are summarized in Table 3.

***Table 3.*** *Carbon emission calculations during the construction phase for three types of tunnel*

| **Tunnel type** | **Length (m)** | **$CO_2$ emissions (t CO2)** | **Unit length $CO_2$ emissions (t CO2/m)** |
|---|---|---|---|
| Immersed tunnel | 4799 | 329260.92 | 68.61 |
| Drill-and-blast tunnel | 9534 | 257970.52 | 27.06 |
| Shield tunnel | 4765 | 120688.90 | 25.33 |

The calculations reveal that the shield tunnel has both the lowest total carbon emissions and unit length carbon emissions compared to the other two options. While the drill-and-blast tunnel demonstrates a lower unit carbon emission than the immersed tunnel, its total carbon emissions are slightly higher due to its length being twice that of the others. This highlights the impact that initial design choices, like the construction method, may have on the emission footprint of the overall project. Further note that for the final determination, the selection also needs to consider construction speed, cost, traffic capacity, alignment, construction risks, and local planning. For example, while the shield tunnel has advantages in terms of shorter length and carbon performance, the site presents complex geological conditions. These include fault zones and hard rock strata, which may lead to challenges such as cutter head jamming. Additionally, the shield method for undersea tunnels faces geological risks, including sudden water inflows. Comparatively, the immersed tunnel offers advantages in terms of alignment, structural reliability and a lower risk during construction, although it performs worst in carbon emission. Due to these advantages, the immersed tunnel was actually chosen as the final scheme.

### 3.3. Carbon emission calculation of the operation & maintenance phase

Based on annual power consumption for operations, including ventilation and lighting, the tunnel's yearly electricity use is estimated at 506.32 MWh, with the regional electricity carbon emission factor at 0.5876 kg$CO_2$/kWh. Then assuming a service life of 100 years, the total carbon emissions from electricity consumption for ventilation, lighting, communication, and other electrical equipment are estimated at 29,751.36 tons. Due to the uncertainties involved, maintenance activities are to be estimated. For the immersed tunnel, maintenance activities contribute about 14% of emissions during the operations and maintenance phase, or around 4% of the entire lifecycle (Wu et al., 2024). Therefore, maintenance activities are estimated to result in approximately 4,843 tons of carbon emissions over the 100-year service period. Consequently, the total carbon emissions for the operations and maintenance phase are estimated at 34,594 tons.

### 3.4. Carbon emission distribution in the life cycle

As carbon emissions directly generated during the design phase are minimal, and emissions from the dismantling phase are not considered in this case study, the carbon emission distribution for the immersed tunnel is shown in Figure 3, based on the calculation results from the preceding sections.

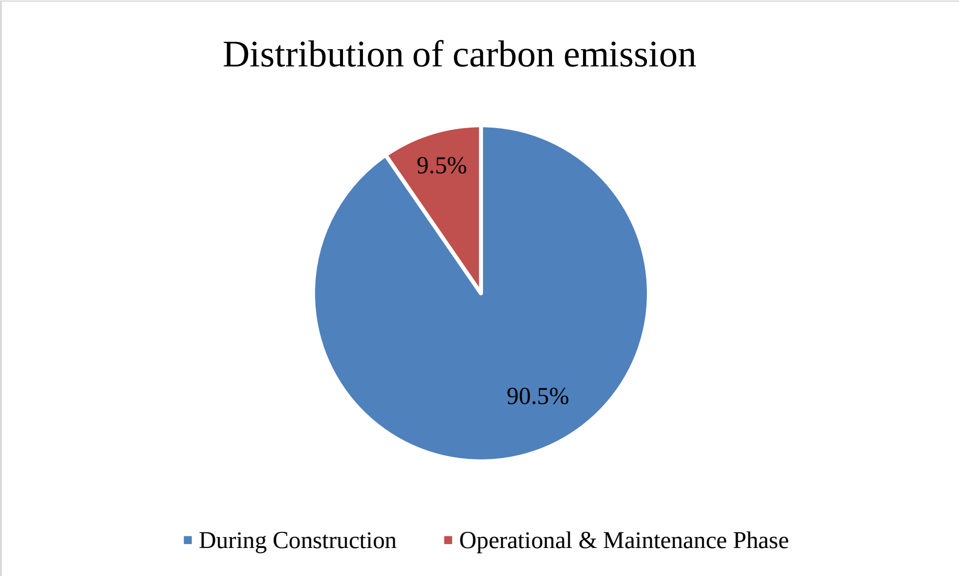


***Figure 3.*** *Percentages of carbon emissions in different phases*

As shown in Figure 3, the majority of carbon emissions from the immersed tunnel occur during the construction phase. In contrast, emissions during the operational period are relatively low. This is mainly due to the implementation of several energy-saving strategies, including an optimized power distribution system, energy-efficient transformers, an LED dimming control system, and a highly efficient ventilation system. However, the emissions generated by the traffic using the tunnel during its lifetime are not considered in this study, nor are they compared with the emission reductions obtained by the improved traffic situation that the tunnel will achieve. Therefore, unlike in the case of metro tunnels where the energy consumption of the trains can be relatively straightforward included in the emission calculations, and has been found to significantly contribute to the overall emissions during the operational phase (Long et al., 2025), the scope of this study does exclude the influence of any traction systems. As a result, the carbon emissions calculated are primarily generated concentrated in the construction phase. A wider scope, including the traffic in the tunnel as well as the traffic avoided in the larger urban area would be needed for a full comparison of the imapct of the tunnel construction. This is beyond the scope of this study.

## 4. APPROACHES TO REDUCING THE CARBON FOOTPRINT OF TUNNELS

Achieving low-carbon tunnel infrastructure begins with strategic interventions at the design stage, where decisions have long-term implications for material demand and energy consumption. One of the most effective approaches is to minimize the use of carbon-intensive materials such as cement and steel. This approach can be realized by optimizing tunnel cross-sectional dimensions, reducing reinforcement ratios, and adopting thin lining designs, which have been shown to significantly lower embodied carbon (Spyridis & Bergmeister, 2024). In addition, the use of prefabricated and modular structures helps reduce material waste and on-site energy consumption, particularly when combined with LCA and sensitivity analysis to inform design decisions. The integration of digital tools, such as building information modeling (BIM), machine learning, and LCA platforms, further enhances the potential to refine structural configurations and reduce carbon footprints. On the material side, substituting ordinary Portland cement with low-carbon alternatives such as fly ash or slag-based binders can yield considerable emission savings (Barbhuiya et al., 2025), while the use of recycled steel and high-recycled-content concrete contributes further benefits (Guo et al., 2025). Novel materials such as geopolymer concrete and foam glass panels are also under exploration for their low-carbon potential. In terms of tunnel structures, innovations like sprayed concrete linings and spray-applied waterproof membranes have demonstrated both technical reliability and carbon reduction advantages (Peñaloza et al., 2024). These material and structural adjustments collectively offer significant opportunities to decarbonize tunnel construction.

Beyond construction, operational emissions, particularly in metro tunnel systems, are largely driven by traction power and electromechanical systems such as lighting, ventilation, and climate control. For instance, traction energy alone may account for up to 84% of operational-phase greenhouse gas emissions (Da Fonseca-Soares et al., 2023). To mitigate these impacts, energy-efficient technologies such as LED lighting, intelligent control systems, and regenerative braking should be implemented. Moreover, integrating renewable energy sources (such as solar and wind) into tunnel systems can further reduce reliance on fossil-based electricity. Architectural interventions, such as optimizing the vertical profile of stations, particularly through U-shaped or parabolic designs, have been shown to improve energy efficiency by facilitating gravity-assisted acceleration and braking (Xin et al., 2014). During the end-of-life phase, although its contribution to total emissions is relatively low, carbon reduction can still be achieved by increasing the recycling rate of construction waste, shortening transportation distances, and minimizing fuel consumption through improved demolition methods. Establishing a pre-demolition material inventory and tracking system can also enhance the efficiency of resource recovery. Altogether, a comprehensive life-cycle strategy encompassing design, construction, operation, and dismantling is essential to low-carbon tunnel infrastructure.

## 5. CONCLUSION

This study highlights the importance of life cycle assessment of carbon emissions in tunnels. While existing research tends to focus on individual stages, comprehensive full life cycle studies remain limited. To address this gap, this paper presents a synthesis of current low-carbon tunnel practices, including: (1) methodologies for quantifying emissions across all life stages; (2) a case study highlighting differences among various tunnel types and the corresponding carbon emission distribution; and (3) practical strategies for reducing emissions. The aim of this study is to serve as a reference for engineers, planners, and decision-makers, aiming to contribute to the carbon neutrality in underground engineering.

Although the proposed computational framework is applicable at the project level, several important areas remain open for future investigation. First, there is an urgent need to establish standardized and cross-sectoral protocols for setting the calculation boundaries, aiming a consistent and accurate emission accounting across industries. Second, the statistics of engineering activities in the operational and maintenance phase, as well as the dismantling phase, should be further collected to finalize the carbon emission calculation in the full life cycle of tunnels. Finally, the development of digitally integrated, regionally scalable emission accounting systems may further enhance the efficiency and transparency of carbon tracking and decision-making in underground infrastructure projects.

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