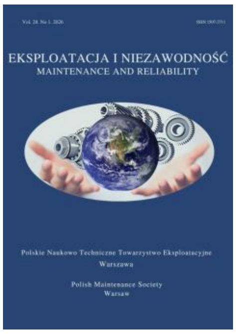

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Optimization of electric concrete transport vehicle configuration for long-distance tunnel construction considering driving range: a case study

Indexed by: Web of Science Group

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Highlights

- Driving range critical for ECTV optimization in tunnels.
- Seasonal changes impact ECTV deployment significantly.
- Increased excavation distance raises ECTV requirements.
- Balancing load capacity and range enhances efficiency.
- Case study validates model in plateau conditions.

Abstract

This study optimizes the configuration of Electric Concrete Transport Vehicles (ECTVs) for long-distance tunnel construction, focusing on the critical factors of driving range and reliability. A comprehensive model integrating tunnel length, terrain, construction schedules, vehicle load capacities, driving range, and reliability is developed. The study acknowledges limitations of traditional fuel-powered vehicles and proposes ECTVs as a sustainable and reliable alternative. The model is validated through a case study in a plateau region of Southwest China. Key findings show that the number of ECTVs required increases with excavation distance, seasonal variations significantly impact configuration, and balancing loading capacities with driving range and reliability is crucial for optimization. The study contributes a new approach to ECTV configuration by incorporating driving range and reliability into the model, offering practical guidance for construction managers to reduce costs, minimize delays, enhance efficiency, and improve reliability. Further research is needed to address model limitations.

Keywords

long-distance tunnel; driving range; electric concrete transport vehicle; configuration

1. Introduction

Long-distance tunnels have become an essential solution for overcoming geographical barriers, facilitating transportation in regions with difficult terrain, and significantly reducing travel distances [1]. Concrete plays a vital role in ensuring the structural stability and safety of tunnel systems, making its efficient transportation essential to the success of tunnel construction. The effectiveness of concrete delivery directly influences both the progress and quality of tunnel support structures [2-4]. As such, optimizing concrete transportation is a key factor in controlling construction timelines, costs, and overall project efficiency [5,6].

Traditional fuel-powered vehicles have long been used for transporting concrete in tunnel construction. However, they pose environmental sustainability, operational efficiency, and reliability challenges. These vehicles emit significant pollutants, contributing to air pollution, and generate high noise levels, which adversely affect the working environment and the health of construction workers [7-9]. Additionally, their fuel

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consumption and maintenance costs are substantial [10]. Operating fuel-powered vehicles in long-distance tunnels also strains ventilation systems, which are vital for maintaining air quality and ensuring worker safety [11]. These limitations make fuel-powered vehicles increasingly incompatible with the green, low-carbon, and reliable objectives of contemporary infrastructure projects [12,13].

Electric Concrete Transport Vehicles (ECTVs) have emerged as a promising alternative to address these challenges. ECTVs offer several advantages, including zero emissions, low noise levels, superior energy efficiency, and improved reliability, making them more suitable for modern construction practices [14-16]. They enhance the working environment within tunnels and alleviate strain on ventilation systems, which are essential for air quality and worker safety [17]. Their environmentally friendly nature aligns with global sustainability initiatives and helps meet stringent emissions regulations in construction projects [18,19]. Moreover, their improved reliability can reduce downtime and increase operational efficiency, making them attractive for long-distance tunnel construction.

Despite these benefits, the widespread adoption of ECTVs in long-distance tunnel projects faces technical limitations, particularly driving range. In long-distance tunnel construction, concrete transportation may involve extensive travel over isolated or challenging terrain with limited charging infrastructure, restricting their operational efficiency and raising concerns about meeting project demands with strict timeframes and geographical challenges [23-25]. Therefore, ensuring ECTVs can operate effectively over extended distances, under varying conditions, and with high reliability is critical for their adoption in tunnel construction.

Advances in battery technologies and charging infrastructure have made the use of ECTVs more feasible. As battery performance improves and charging stations become more widely available, the limitations imposed by driving range are gradually being addressed. However, the full potential of ECTVs can only be realized by developing optimized configuration models that take into account not only the driving range but also the specific requirements of tunnel construction projects, including reliability. These include the tunnel length, terrain, construction schedules, vehicle load capacities, and other operational factors. To this end, the development of comprehensive configuration models is crucial for determining the optimal deployment of ECTVs in long-distance tunnel construction.

This study aims to bridge this gap by developing a comprehensive configuration model for ECTVs. The model integrates multiple factors, including driving range, tunnel length, construction demands, and reliability, to provide scientific and practical guidance for vehicle deployment. The key innovations of this research include: (1) incorporating driving range and reliability as central variables in the configuration model, allowing for an accurate reflection of long-distance tunnel characteristics; (2) introducing multi-dimensional constraints, such as construction schedules and vehicle performance, to enhance the model's applicability and precision; and (3) validating the model through a case study in a plateau region, ensuring its relevance to real-world applications.

The paper is structured as follows: Section 2 presents a comprehensive review of existing literature related to the optimization of electric vehicles for construction tasks, with a focus on long-distance tunnel construction and reliability. Section 3 details the methodology, explaining the development of the configuration model, assumptions, constraints, and objective functions. Section 4 describes the case study, including the project background, environmental conditions, and model parameters. Section 5 presents the analysis of configuration results for both the main and parallel pilot tunnels, considering varying operational conditions and highlighting the impact of seasonal changes on vehicle deployment and reliability. Finally, Section 6 provides a discussion of the findings, exploring practical applications, limitations, and implications. Section 7 concludes the paper by summarizing the key results and suggesting directions for future research. This study aims to provide construction managers with a scientific basis for deploying Electric Construction Transport Vehicles (ECTVs) in long-distance tunnel projects, offering practical guidance to reduce costs, minimize delays, enhance overall construction efficiency, and improve reliability.

2. Literature review

2.1. Electric vehicles in construction

The construction industry is increasingly embracing electric vehicles (EVs) due to growing concerns over environmental sustainability, energy consumption, and operational efficiency. Traditionally, construction machinery relied on internal combustion engines (ICEs), which contribute significantly to air pollution, noise, and high operational costs. As environmental regulations become more stringent and sustainability goals become central to infrastructure development, the adoption of electric construction vehicles (ECVs) has emerged as a viable alternative.

Electric Construction Vehicles (ECVs) include a wide range of machinery, such as electric excavators, bulldozers, loaders, forklifts, cranes, and road rollers. These vehicles offer numerous advantages over their ICE counterparts, including reduced emissions, lower noise levels, and smoother operation, making them particularly suitable for construction sites where air quality and worker safety are of utmost concern, especially in enclosed environments like tunnels. For example, Tong et al.[18] provide a comprehensive review of the key technologies and future directions in the development of electric construction machinery in China, highlighting the significant benefits of electric drive systems in reducing both emissions and noise. These advantages are especially evident in long-distance tunnel projects, where the use of fuel-powered vehicles is associated with environmental degradation, poor air quality, and noise pollution, all of which negatively impact worker health and safety[26].

One of the key components that influences the performance of ECVs is the Energy Storage Unit (ESU), typically comprising batteries, supercapacitors, or fuel cells. He and Jiang[27] discuss various hybrid energy storage (HES) structures tailored for construction machinery, emphasizing the need for selecting an appropriate ESU based on vehicle power demand, weight, and operational conditions. Lin et al.[14] further elaborate on the advancements in battery technologies, specifically addressing the importance of battery management systems (BMS) to enhance reliability, extend battery life, and optimize energy consumption.

The efficient operation of ECVs also depends heavily on the development of robust charging infrastructure. As the deployment of ECVs grows, the availability of charging stations becomes critical to supporting their widespread use. Studies by Jordán et al., [28]and Lin et al. [14]focus on the optimal placement of charging stations within construction sites, utilizing simulation models and optimization algorithms to determine ideal locations for charging infrastructure. These models take into account factors such as vehicle mobility patterns, traffic density, and the spatial layout of construction sites to ensure efficient and convenient charging, thereby minimizing downtime.

Despite these advancements, several technical challenges remain, particularly in long-distance tunnel construction, where limited access to charging infrastructure, extreme environmental conditions, and the demanding energy requirements for concrete transport present significant barriers to the widespread adoption of ECTVs[29]. Therefore, optimizing the configuration of ECTVs becomes a crucial step in overcoming these challenges and ensuring their practical application in such environments.

2.2. Optimization models for electric vehicles configuration

In the context of long-distance tunnel construction, the adoption of Electric Concrete Transport Vehicles (ECTVs) presents a unique set of challenges that can be addressed through the development of optimized configuration models. These models aim to enhance the performance, efficiency, and sustainability of ECTVs, considering factors such as transportation distance, terrain, operational time, vehicle load, energy consumption, and environmental conditions.

Static and Dynamic Layout Planning are two primary approaches for optimizing the configuration of construction vehicles. Static layout planning involves assigning facilities to fixed locations throughout the construction period, while dynamic layout planning allows for the relocation of facilities between stages of the construction process[27]. Huang et al. [30]propose a multi-objective optimization approach to improving the operational performance of electric construction machinery systems, suggesting that both static and dynamic aspects must be considered to ensure optimal vehicle configuration. By considering transportation distances, operational time, and costs, they develop a model that can enhance ECTV performance while balancing project constraints.

Various optimization techniques have been applied to solve configuration problems in construction vehicle deployment.

Heuristic models, such as genetic algorithms (GA), particle swarm optimization (PSO), and simulated annealing (SA), are widely used to solve complex, real-world problems. These models are effective in finding near-optimal solutions within a reasonable time frame. On the other hand, exact optimization models, such as mixed-integer linear programming (MILP) and mixed-integer nonlinear programming (MINLP), provide optimal solutions but are computationally more expensive and complex to implement. Huang et al. [31]highlight the advantages and limitations of both heuristic and exact models, demonstrating how each can be applied to optimize ECTV configurations based on different project requirements.

The multi-objective nature of ECTV configuration is another critical consideration in optimization modeling. ECTVs must operate efficiently across several conflicting objectives, such as minimizing transportation costs, maximizing energy efficiency, reducing emissions, and meeting construction deadlines. Multi-objective optimization techniques, such as Pareto-front optimization, are useful in generating a set of optimal solutions that balance these competing objectives. These methods allow decision-makers to select the best configuration based on project-specific priorities, such as cost, sustainability, or operational efficiency [32]. By applying these algorithms, construction managers can choose the most suitable ECTV configuration that aligns with the goals of the project.

Real-world construction environments are inherently uncertain, and factors such as material demand fluctuations[33], equipment breakdowns[34], and weather conditions[35] should be incorporated into optimization models to enhance their robustness. Optimization models for ECTV configuration that account for these uncertainties can help ensure the practicality and feasibility of the proposed solutions. Stochastic optimization models, for example, have been employed to consider uncertainties in key variables like battery capacity, charging time, and vehicle performance[36]. These models generate solutions that are less sensitive to variations in input parameters, thereby improving the reliability and robustness of the optimization process.

Another important area of research is the integration of charging infrastructure into optimization models for ECTV deployment. In long-distance tunnel construction, the availability and strategic placement of charging stations are critical factors for ensuring the continuous operation of ECTVs[37]. Several studies have proposed models that optimize the placement of charging stations, taking into account factors such as vehicle range, construction schedules, and geographical constraints[38,39]. These models aim to minimize downtime and maximize operational efficiency by ensuring that vehicles can be charged efficiently while maintaining high productivity levels.

3. Methodology

3.1. Work scenario description

In the complex operational environment of tunnel construction, concrete pouring serves as the core process for structural support and shaping. Its efficient and continuous execution is critical to ensuring project progress and the safety of quality standards.

Figure 1 illustrates the working scenarios of electric concrete transport vehicles(ECTVs) in tunnel construction, described in detail as follows:

Loading: After the concrete pouring process begins, the concrete transport vehicle, following dispatch instructions, travels from the parking lot to the concrete mixing station for loading.

Transporting: Once fully loaded, the transport vehicle delivers the concrete from the mixing station to the designated work site.

Unloading: At the work site, the transport vehicle connects to the concrete pump. The concrete pumping system in the vehicle is activated, pumping the concrete to the work site at a constant pressure and flow rate.

Returning: If additional concrete pouring tasks remain and the battery level is sufficient, the transport vehicle returns to the concrete mixing station to await the next loading task.

Charging: If the current cycle of concrete pouring is complete or the battery is depleted, the vehicle returns to the parking lot for charging, preparing for the next cycle of the concrete pouring process.

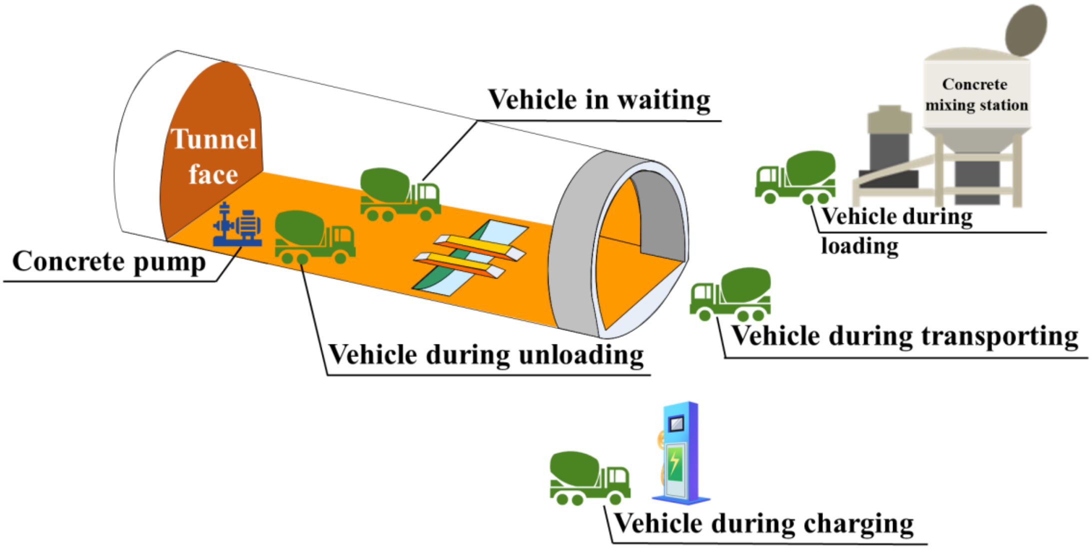

Fig. 1. Tunnel electric concrete transport vehicles working scene.

To address the configuration issues of electric concrete transport vehicles in long-distance tunnels more effectively, the following sections will provide a detailed description of our model development process. This model is designed to comprehensively account for the characteristics of tunnel construction, the performance limitations of electric concrete transport vehicles, and various practical constraints, thereby offering optimized strategies for configuring electric concrete transport vehicles in long-distance tunnel projects. To visualize the overall framework and key components of the model development process, Fig. 2 presents a schematic overview that integrates the various constraints, assumptions, and optimization objectives discussed in this section.

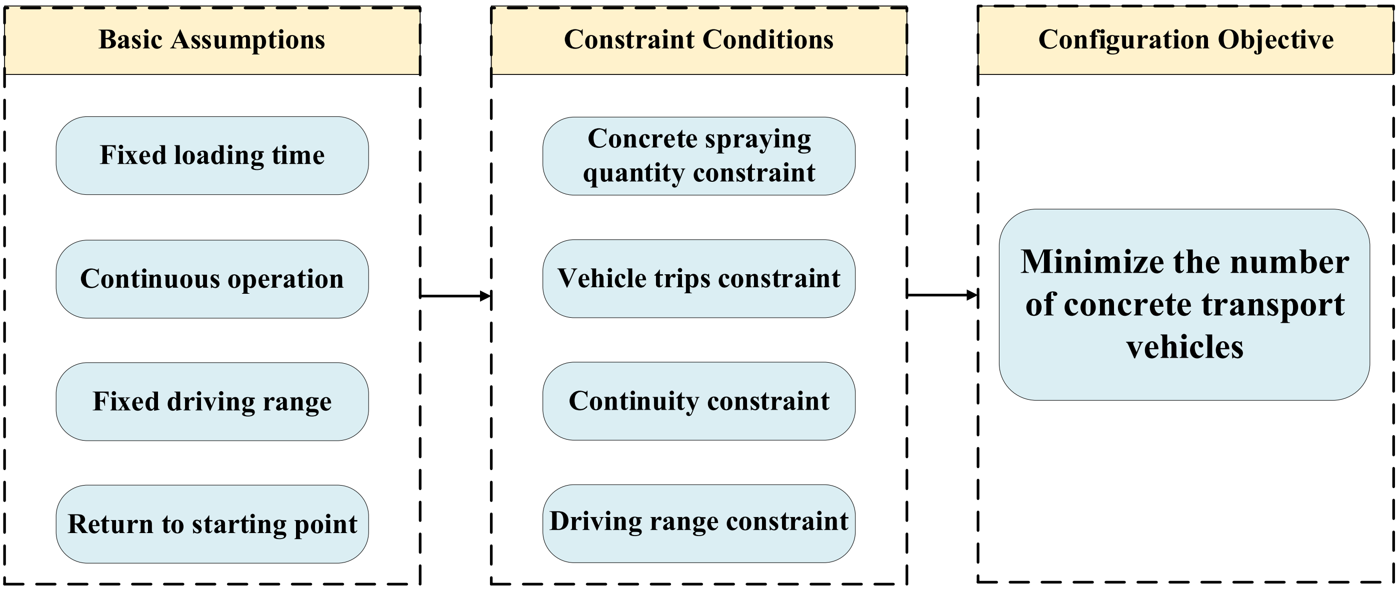

Fig. 2. Overall framework of the proposed methodology.

3.2. Model development

3.2.1. Basic assumptions

The following basic assumptions are proposed in this study to focus on the research problem and simplify the modeling process:

1) Fixed loading time

It is assumed that the time required for each concrete transport vehicle to be fully loaded with concrete is constant and unaffected by external factors such as equipment performance or operator proficiency.

2) Continuous operation

The concrete transport vehicles are assumed to operate continuously during their working hours, without considering interruptions caused by equipment failure, maintenance, or other factors.

3) Fixed driving range

Each vehicle's driving range is treated as a fixed value, unaffected by factors such as battery degradation, road conditions, or driving habits.

4) Return to starting point

After completing each concrete pouring task, all transport vehicles are assumed to return to their starting point (i.e., the parking lot) for charging. It is assumed that the charging facilities are sufficient to fully recharge all vehicles before the next concrete pouring task begins, ensuring uninterrupted operations.

These assumptions provide the foundation for building and optimizing the model while simplifying the complexities of the actual construction process. This enables us to focus on studying and addressing core issues. However, it should be noted that these assumptions may deviate from real-world conditions. Therefore, when applying the model to practical engineering projects, appropriate adjustments and validations should be made based on actual circumstances.

3.2.2. Constraint conditions

1) Concrete spraying quantity constraint

The concrete spraying quantity is crucial to ensuring the progress and quality of tunnel construction. Concrete spraying is a preliminary support measure implemented after tunnel excavation. This process stabilizes the working face, preventing collapses and spalling. The total quantity of sprayed concrete in each cycle is determined by the spraying specification and the excavation advance per cycle, as expressed by the following formula:

$$Q = \beta \times l \tag{1}$$

Where:

Q: Total quantity of sprayed concrete per cycle (unit: m³);

β: Spraying specification, defined as the volume of concrete required per meter of tunnel length (unit: m³/m);

l: Excavation advance per cycle, representing the length of tunnel excavated in each cycle (unit: m).

2) Vehicle trips constraint

The vehicle trips constraint focuses on balancing construction demands and transportation capacity. The total amount of concrete to be poured during construction, combined with the single-trip loading capacity of the concrete transport vehicle, determines the minimum required number of vehicle trips. To satisfy this constraint, the total number of trips required to complete a full concrete pouring task must be calculated based on the transport vehicle's loading capacity and the total volume of concrete for the task. The actual number of vehicle trips allocated must be greater than or equal to this minimum threshold, expressed as:

$$N_{\text{trips}} \geq \left\lceil \frac{Q}{C} \right\rceil \tag{2}$$

Where:

N_{trips}: Total number of required vehicle trips;

C: Single-trip loading capacity of the concrete transport vehicle (unit: m³).

3) Continuity constraint

The continuity constraint focuses on coordination and efficiency within the construction workflow, ensuring that concrete pouring can proceed uninterrupted and unnecessary vehicle waiting times are avoided. To achieve this, precise scheduling of vehicle dispatch and operations is required. When the N-1-th vehicle begins unloading concrete, the N-th vehicle should already be ready and waiting. Additionally, when the N-th vehicle starts unloading, the first vehicle in the next cycle (1-st vehicle) should have completed loading and arrived at the waiting area near the worksite, ready for the next round of unloading. This can be expressed as:

$$N_{\text{vehicles}} \times t_{\text{unload}} \geq T_{\text{round-trip}} \tag{3}$$

Where:

N_{vehicles}: Total number of vehicles required

$T_{\text{round-trip}}$: Round-trip cycle time for a concrete transport vehicle, calculated as:, $T_{\text{round-trip}} = 2 \times \left(\frac{L_{\text{inner}}}{V_{\text{inner}}} + \frac{L_{\text{outer}}}{V_{\text{outer}}}\right) + \left(\frac{t_{\text{load}}+t_{\text{unload}}}{60}\right)$ (unit: h);

t_{load}: Loading time (unit: min);

t_{unload}: Unloading time (unit: min);

L_{inner}: Distance inside the tunnel, from the portal to the worksite $L_{\text{inner}} = \sum l$ (unit: km);

L_{outer}: Distance outside the tunnel, from the portal to the concrete mixing station (unit: km);

V_{inner}: Average speed inside the tunnel (unit: km/h);

V_{outer}: Average speed outside the tunnel (unit: km/h).

4) Driving range constraint

The driving range constraint is a critical factor in ensuring the continuity and efficiency of construction operations. The round-trip distance for each electric concrete transport vehicle must fall within its driving range to avoid disruptions caused by battery depletion. Additionally, it is assumed that all vehicles start each concrete pouring cycle with a fully charged battery. This constraint is expressed as:

$$D_{\text{range}} \geq 2 \times (L\text{inner} + L\text{outer}) \tag{4}$$

Where:

D_{range}: Driving range of the electric concrete transport vehicle (unit: km).

If this constraint is not met before the start of a concrete pouring cycle, it indicates that the electric concrete transport vehicles are unsuitable for the given operating conditions due to driving range limitations. Alternative solutions must be considered, such as using fuel-powered concrete transport vehicles or relocating the concrete mixing station to a closer location.

These constraints collectively define the core requirements for the concrete pouring process: the concrete spraying quantity constraint ensures that the sprayed concrete is fully applied in each cycle, maintaining construction safety; the vehicle trips constraint guarantees sufficient transportation capacity to meet the concrete pouring demand; the continuity constraint ensures seamless coordination between construction phases, enabling efficient and uninterrupted workflows; and the driving range constraint ensures the stable operation of electric concrete transport vehicles, preventing disruptions due to battery depletion. Together, these constraints ensure the efficiency, continuity, safety, and stability of the concrete pouring process. In practical engineering applications, this model can be further adjusted and optimized to accommodate specific project conditions and requirements.

3.2.3. Configuration objective

The primary objective is to minimize the number of concrete transport vehicles required, thereby reducing costs while ensuring the continuity of the concrete pouring process. The objective function can be defined as follows:

Number of concrete trucks required

$$N_{\text{vehicles}} = \left\lceil \frac{N_{\text{trips}}}{R_{\text{round-trip}}} \right\rceil \tag{5}$$

Where: $R_{\text{round-trip}}$: The maximum number of round trips each vehicle can make based on its driving range.

$$R_{\text{round-trip}} = \left\lfloor \frac{D_{\text{range}}}{2 \times (L_{\text{inner}} + L_{\text{outer}})} \right\rfloor \tag{6}$$

This objective ensures an optimal balance between minimizing operational costs and maintaining the continuity and efficiency of the construction process.

4. Case study

The case study focuses on a tunnel construction project located in the plateau region of Southwest China, selected for its challenging geographical and environmental conditions. These unique features provide a valuable basis for analyzing the configuration and deployment of electric concrete transport vehicles (ECTVs) in long-distance tunnel construction projects. This section outlines the key parameters of the project, the difficulties faced, and how these conditions shape the strategies for efficient vehicle deployment.

4.1. Case description and background

The tunnel project is situated in a high-altitude plateau region with an average elevation of 3,500 meters. This environment is characterized by thin air, extreme temperature fluctuations, and occasional snowfall, all of which significantly affect both vehicle performance and construction operations. Traditional fuel-powered vehicles struggle in such conditions, particularly with fuel efficiency and engine power in low oxygen environments. Electric vehicles, while offering environmental benefits, also face challenges in cold temperatures that can reduce battery efficiency and range.

This tunnel forms part of a broader infrastructure project aimed at improving transportation links in Southwest China, particularly in mountainous and remote areas. The construction of this tunnel is vital for enhancing transportation efficiency and safety, facilitating the movement of goods and people through a previously inaccessible region. The tunnel itself is a single-bore, double-track structure, approximately 11 kilometers in length, and serves as a crucial link in the regional transport network.

Given the high energy demands of the construction process and the reduced driving range of ECTVs in cold temperatures, a robust charging infrastructure is essential. A charging station has been installed at the parking lot near the concrete mixing station, capable of fully charging each ECTV in 1.5 hours. The strategic placement of this charging station ensures that vehicles can be charged efficiently during non-pouring periods, minimizing downtime and maximizing operational efficiency.

The availability and capacity of the charging infrastructure significantly impact vehicle deployment. In this case, the charging station's location and charging speed allow for a continuous flow of operations, as vehicles can be charged and dispatched quickly to meet construction demands. However, in scenarios where charging infrastructure is limited or charging times are longer, more vehicles may be required to ensure continuous operations, increasing the overall project costs.

Project Scale and Structure: The tunnel is a single-bore, double-track tunnel with a total section length of approximately 11 km. The surrounding rock is primarily classified as Grade III. The average advance per cycle in the main tunnel is about 1.8 m, with a spraying specification of 28 m^3/m. A parallel pilot tunnel is located on the right side of the main tunnel, with an average advance per cycle of about 2.4 m and a spraying specification of 16 m^3/m.

Geographical and Environmental Features: The project is located at an average elevation of 3,500 meters above sea level, posing significant challenges for both construction operations and vehicle performance. The plateau environment is marked by thin air, reduced atmospheric pressure, and large temperature variations, all of which can reduce the performance of internal combustion engines and impact the battery efficiency of electric vehicles. These environmental challenges require careful consideration of how ECTVs will function, particularly when factoring in the energy efficiency and operational time limits imposed by battery range.

Concrete Transportation Distance: The concrete mixing station is located approximately 6.5 km from the tunnel portal, with the parking lot situated at the mixing station. The route between the tunnel portal and the mixing station has been artificially leveled, ensuring a smooth, even path without any steep inclines.

Equipment Selection: Considering environmental protection and efficiency requirements, the construction team employs electric concrete transport vehicles (ECTVs) produced by leading domestic manufacturers. These vehicles are equipped with 10 m^3 drum mixers, which provide the necessary capacity to meet the concrete transportation demands of the construction process. This corresponds to the single-trip loading capacity (C) of the vehicles, as defined in the model, where each vehicle can carry 10 m^3 of concrete per trip.

Operational Parameters: Based on on-site construction logs, the average speed inside the tunnel is 5 km/h, while outside the tunnel it is 25 km/h. The average unloading time per vehicle is 30 minutes, and the average loading time is 20 minutes. Regarding driving range, the vehicles can travel approximately 90 km on a full charge in summer and 60 km in winter.

In the subsequent sections, this study will explore the configuration results of electric concrete transport vehicles for the main tunnel and the parallel pilot tunnel under different operating conditions. The goal is to optimize vehicle allocation while meeting construction demands, thereby reducing construction costs and improving efficiency. To gain a deeper understanding of the performance and potential challenges of electric concrete transport vehicles in long-distance tunnel projects in plateau regions, this study specifically compares the configuration requirements under summer and winter conditions, offering valuable insights for similar projects.

4.2. Challenges and operational considerations

This project faces several operational challenges that must be addressed to ensure efficient vehicle deployment. First, seasonal battery performance presents a significant issue, as the driving range of the ECTVs decreases in winter due to reduced battery efficiency in cold temperatures. This requires careful planning to ensure sufficient vehicles are available to maintain continuous operations during the colder months. Although the terrain is relatively flat, the tunnel length and excavation rate introduce logistical challenges, necessitating an increase in the number of vehicles as excavation distances grow, to ensure uninterrupted concrete pouring. Finally, vehicle capacity must be carefully balanced with operational time. While increasing loading capacity can reduce the number of trips required, it simultaneously reduces driving range, making it essential to find an optimal balance to minimize delays and maintain a sustainable fleet size. These challenges highlight the need for strategic planning and operational flexibility to ensure the efficient and uninterrupted flow of construction activities.

5. Results

5.1. Configuration results for the main tunnel

This section analyzes the configuration requirements for electric concrete transport vehicles in the main tunnel. Utilizing the model developed previously and inputting actual project data, variations in the number of electric concrete transport vehicles (N_{vehicles}) and round trips ($R_{\text{round-trip}}$) are calculated under both summer and winter conditions for different excavation distances.

The following key points are evident from the plotted charts:

Variation in Vehicle Numbers: As the excavation distance increases, the required number of ECTVs shows a gradual increase. This is due to the longer round-trip times resulting from the extended excavation distance, which reduces the transportation efficiency of each vehicle per unit of time (see Figure 3). Therefore, to maintain continuity and efficiency in construction, the number of vehicles must be increased.

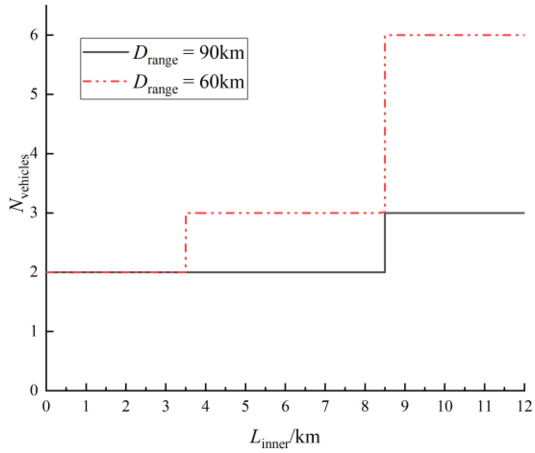

Fig. 3. Relationship between tunnel distance and total number of required vehicles under different driving ranges (main tunnel).

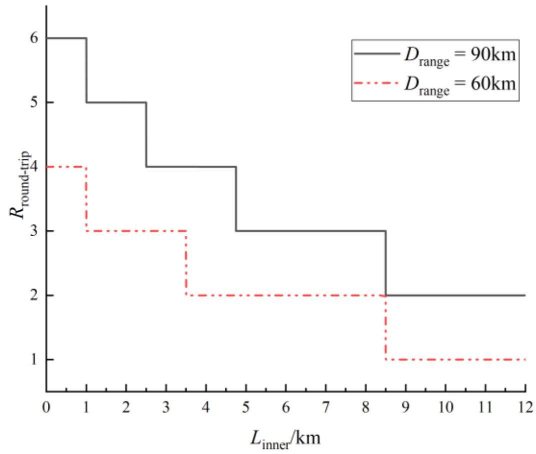

Fig. 4. Relationship between the distance in the tunnel and the maximum round trip times of each concrete transport vehicle with different mileage (main hole).

Variation in Round Trips: As the excavation distance increases, the number of round trips per vehicle decreases. This is because a longer excavation distance means a longer single round-trip time, which reduces the number of round trips that can be completed within the driving range limit of the electric concrete transport vehicle (see Figure 4). This phenomenon plays a significant role in vehicle configuration strategies, especially when considering driving range and transportation efficiency.

Seasonal Impact: The difference in driving range between summer and winter has a significant impact on vehicle configuration. For the same excavation distance, the number of vehicles required in winter is generally higher than in summer. More notably, as the excavation distance increases, the gap in vehicle configuration requirements between summer and winter widens. This indicates that, during long-distance tunnel excavation, the reduced transportation efficiency in winter is more pronounced, requiring more vehicles to ensure construction progress.

5.2. Configuration results for the parallel pilot tunnel

Compared to the main tunnel, the cross-section of the parallel pilot tunnel is smaller, resulting in a relatively lower volume of excavated material per cycle. However, due to the typically narrow entrance of the parallel pilot tunnel, the loading time may be longer. The restricted space limits the operational efficiency of the loading equipment, thus increasing the time required to load each vehicle. The analysis of the configuration results reveals the following key points:

Variation in Vehicle Numbers and Round Trips: Similar to the main tunnel, as the excavation distance increases, the number of electric concrete transport vehicles (ECTVs) required also increases (see Figure 5).

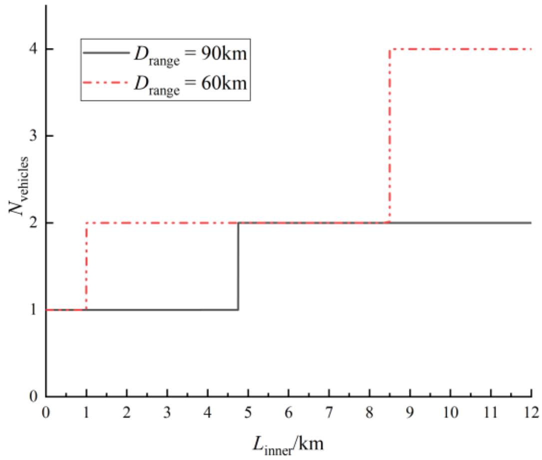

Fig. 5. Relationship between the distance in the tunnel and the total number of vehicles required under different mileage (parallel pilot tunnel).

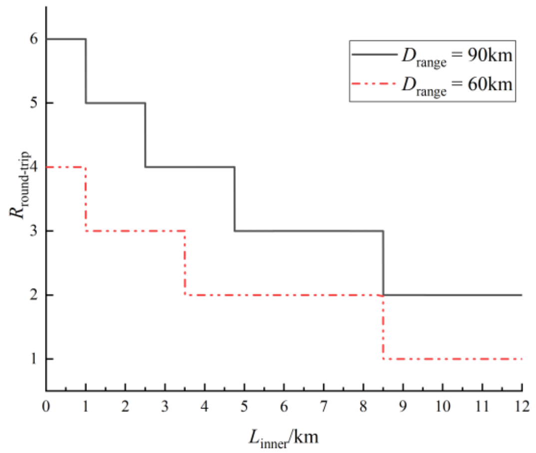

Fig. 6. Relationship between the distance in the tunnel and the maximum round trip times of each concrete transport vehicle with different mileage (parallel pilot tunnel).

Furthermore, it is observed that in both the main and parallel pilot tunnels, once the excavation distance exceeds a certain threshold, a notable increase in the number of vehicles is required, while the number of round trips decreases correspondingly. This suggests the existence of a common excavation distance threshold, beyond which transportation demand rises for both tunnel types (see Figures 4 and 6). This is due to the significant increase in round-trip times beyond this threshold, which, under the constraint of vehicle driving range, reduces the number of round trips each vehicle can complete, necessitating the addition of more vehicles to meet the increased transportation demand.

Similar Trend in Round Trip Calculation ($R_{round\text{-}trip}$): Although the spraying specification (m^3/m) and excavation distance (l) differ between the main tunnel and the parallel pilot tunnel, the trend of change in round trips ($R_{round\text{-}trip}$) is similar for both tunnels. The primary difference is in the spraying specification and excavation volume, but the number of round trips is mainly influenced by the excavation distance and the distance from the concrete mixing station. In both models, round trips decrease gradually as excavation distance increases, with the dominant impact of excavation distance and the distance to the concrete mixing station (L_{outer}) governing the rate of change in round trips. Overall, as excavation distance increases, $R_{round\text{-}trip}$ decreases, and the trend of change in round trips remains similar as the distance from the mixing station increases.

Seasonal Impact: Similar to the main tunnel, the vehicle configuration in the parallel pilot tunnel is also affected by seasonal variations in driving range. In winter, the reduced driving range requires more vehicles to maintain transportation efficiency.

5.3. Expansion analysis

In the previous case, the driving range of the ECTVs decreased from 90 km in summer to 60 km in winter. This change has a significant impact on the configuration of the vehicles. This section aims to explore how adjusting the loading capacity of the concrete transport vehicles can mitigate the impact of the reduced driving range on vehicle configuration.

Referring to the application of diesel concrete transport vehicles on-site, when the loading capacity (C) is 15 m³, the average unloading time per vehicle in the main tunnel is 45 minutes, with a loading time of 30 minutes. Since ECTVs with a 15 m³ loading capacity are not yet available on-site, the unloading time of the corresponding diesel concrete transport vehicle is substituted into the model for calculation. It is assumed that, under this scenario, the driving range of the electric vehicle is reduced to 45 km.

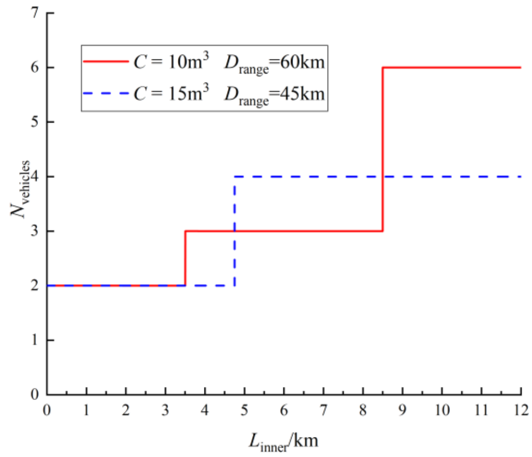

Fig. 7. Relationship between the distance in the tunnel and the total number of vehicles required under different loading capacities (main hole)

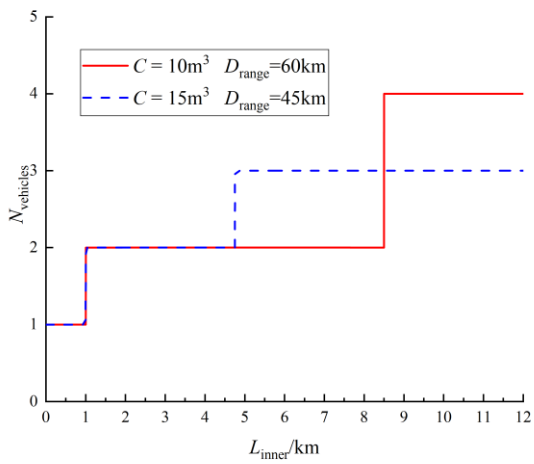

Fig. 8. Relationship between the distance in the tunnel and the total number of vehicles required under different loading capacities (parallel pilot tunnel).

In this scenario, the impact of different loading capacities on the vehicle configuration requirements for both the main tunnel and parallel pilot tunnel is compared. As shown in the charts (see Figures 7 and 8), it is evident that increasing the loading capacity is not always the most optimal solution. In some cases, increasing the loading capacity leads to a further reduction in the electric vehicle's driving range, which in turn forces an increase in the number of vehicles. This indicates that the strategy of increasing the loading capacity needs to strike a balance between improving transportation efficiency and ensuring transportation safety.

Therefore, in practical applications, the vehicle configuration strategy should comprehensively consider various factors, such as excavation distance, loading capacity, and driving range, in order to develop the optimal vehicle configuration plan.

6. Discussions

This study aimed to optimize the configuration of electric concrete transport vehicles (ECTVs) for long-distance tunnel construction, with particular emphasis on reliability under driving range constraints. The key findings indicate that the number of ECTVs required increases with excavation distance, highlighting the critical role of vehicle reliability in maintaining continuous operations as distances extend. The round-trip frequency decreases as the driving range of the vehicles is approached, posing a reliability challenge that must be addressed through strategic vehicle allocation. Additionally, seasonal variations, particularly the reduced driving range in winter, significantly impact vehicle configuration, demanding a greater number of vehicles to ensure reliable construction progress under harsh conditions. Finally, the study suggests that while increasing the loading capacity of vehicles can reduce the number of trips, it also results in a decrease in driving range, introducing a trade-off between transport efficiency and operational reliability.

When compared with previous research, this study provides a more comprehensive approach to ECTV configuration by integrating driving range and reliability considerations as central factors, whereas many past studies focused mainly on technical aspects of electric vehicle performance or specific conditions. For instance, research by Lin et al. [14] and Huang et al. [8] highlighted the technical feasibility of electric vehicles in tunnel construction but did not extensively consider the reliability implications of operational constraints such as driving range and seasonal variations. This study advances the field by systematically addressing the impact of these factors on vehicle deployment, offering a more realistic and practical approach to reliable vehicle configuration under varying construction conditions.

To address the challenge of reduced driving range in winter, several potential solutions can be considered. First, the adoption of advanced battery heating systems can help maintain optimal battery temperatures in cold weather, thereby improving battery efficiency and extending the driving range. Second, the implementation of a more extensive and strategically located charging infrastructure can ensure that vehicles can be charged more frequently and efficiently, reducing the impact of reduced driving range. Additionally, the use of predictive algorithms to forecast weather conditions and adjust vehicle schedules accordingly can optimize vehicle deployment and minimize downtime. Finally, the development of batteries with improved cold-weather performance or the exploration of alternative energy sources, such as hydrogen fuel cells, could provide longer-term solutions to the seasonal variation challenge.

The adoption of ECTVs offers significant economic and environmental benefits compared to traditional fuel-powered vehicles. Economically, ECTVs can lead to substantial cost savings over their lifespan due to lower fuel and maintenance costs. Electric vehicles have fewer moving parts and require less frequent maintenance, reducing downtime and associated costs. Additionally, many governments offer incentives for the adoption of electric vehicles, such as tax credits or rebates, further enhancing their economic attractiveness.

Environmentally, the benefits of ECTVs are equally compelling. By eliminating tailpipe emissions, ECTVs contribute to improved air quality and reduced greenhouse gas emissions, aligning with global sustainability goals. The reduction in noise pollution also enhances the working environment for construction workers and minimizes the impact on surrounding communities. Furthermore, the use of ECTVs supports the transition to a more sustainable and low-carbon construction industry, promoting long-term environmental stewardship.

However, several limitations must be noted. First, the study’s assumptions about fixed loading times, continuous operation, and consistent driving range may not fully capture real-world variability, which could affect system reliability in practice. Factors such as vehicle performance degradation, variations in road conditions, and unforeseen delays could compromise reliability by disrupting vehicle efficiency and scheduling. Additionally, the study primarily focuses on a single tunnel case in Southwest China, which may not fully account for the diversity of conditions in other geographic regions or tunnel types. Thus, the reliability conclusions drawn here may require validation in broader contexts.

To address these limitations, future research could consider dynamic models that incorporate real-time reliability metrics, such as fluctuating vehicle performance, variable battery efficiency, and disruptions in construction schedules. Further studies could also explore a broader range of case studies to validate the generalizability of reliability-focused configurations across different geographical regions, tunnel designs, and climate conditions. Moreover, it would be beneficial to investigate how advancements in battery technology, such as longer-lasting batteries or faster charging systems, could enhance reliability and influence vehicle configuration strategies.

In terms of future research, one promising direction would be to integrate real-time reliability monitoring and optimization techniques into the model, allowing for dynamic adjustments based on actual operational conditions. Additionally, exploring the integration of ECTVs with other construction technologies, such as autonomous vehicles or AI-driven logistics management systems, could lead to more reliable and efficient vehicle deployment strategies.

In summary, while this study provides valuable insights into the optimal configuration of ECTVs for long-distance tunnel construction, it also highlights areas for further improvement in ensuring operational reliability. By addressing the limitations outlined and incorporating more dynamic, real-world factors, future research could offer even more robust guidelines for reliable deployment of electric vehicles in tunnel construction projects.

7. Conclusion

This study presented a comprehensive model for the configuration of electric concrete transport vehicles (ECTVs) in long-distance tunnel construction, with a focus on optimizing vehicle deployment while ensuring reliability under driving range limitations. The primary objective was to provide a practical framework for selecting the optimal number and configuration of ECTVs based on critical factors such as excavation distance, vehicle performance, and seasonal variations in driving range. The study’s key findings suggest that the required number of ECTVs increases with the excavation distance, underscoring the importance of reliability planning as tunnel length grows. Seasonal factors, especially the reduced driving range in winter, significantly impact the configuration, necessitating more vehicles to maintain reliable construction efficiency under adverse conditions. Additionally, the investigation into the impact of loading capacity revealed that while increasing the load can reduce the number of trips, it simultaneously reduces the available driving range, introducing a critical reliability trade-off that must be balanced.

This research contributes significantly to the existing literature by integrating driving range and reliability requirements as central variables in the configuration of ECTVs, an aspect that has been underexplored in previous studies. By considering both technical vehicle performance and operational constraints, this study offers a more holistic approach to reliable electric vehicle deployment in tunnel construction. Specifically, our model explicitly addresses the reliability challenges faced by ECTVs in long-distance tunnel projects, providing a framework for optimizing vehicle configurations that enhance both operational efficiency and system reliability. This is a crucial contribution to the field of Maintenance and Reliability, as it directly impacts the cost-effectiveness and safety of tunnel construction projects. Furthermore, the use of a case study for validation strengthens the model's applicability, though the findings are primarily based on a specific tunnel project in Southwest China, which may limit generalization to other regions or tunnel types. However, the insights gained from this study provide a valuable starting point for future research and practical applications in similar contexts.

In terms of practical implications, the model provides actionable insights for construction managers seeking to enhance reliability while optimizing ECTV usage in long-distance tunnel projects. By accounting for seasonal driving range variations and balancing vehicle loading capacities, construction projects can minimize costs, reduce delays, and improve system reliability. Additionally, the study suggests the need for infrastructure improvements, such as charging stations and advanced battery technologies, to support reliable large-scale adoption of ECTVs.

Although this study provides valuable guidance, it is not without limitations. The assumptions made regarding fixed operational parameters, such as loading time and driving range, do not fully capture real-world variations that might impact reliability due to environmental factors or operational disruptions. Moreover, the focus on a single case study may limit the broader applicability of the model. Future research should address these limitations by incorporating more dynamic and real-time data, considering diverse geographical and operational conditions, and exploring advancements in battery technology and vehicle performance to further improve reliability.

In conclusion, this research advances the understanding of ECTV deployment in long-distance tunnel construction, offering both theoretical and practical insights for achieving reliable electric vehicle operations. By addressing key factors such as driving range and loading capacity, this study provides a solid foundation for optimizing electric vehicle configurations in tunnel projects. Further exploration of the outlined limitations and integration with emerging technologies will be essential for refining reliability-focused strategies and ensuring the successful implementation of electric vehicles in future infrastructure projects.

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Notations

Notation	Meaning	Unit
Q	Total quantity of sprayed concrete per cycle	m³
β	Spraying specification, defined as the volume of concrete required per meter of tunnel length	m³/m
l	Excavation advance per cycle, representing the length of tunnel excavated in each cycle	m
N_{trips}	Total number of required vehicle trips	/
C	Single-trip loading capacity of the concrete transport vehicle	m³
$N_{vehicles}$	Total number of vehicles required	/
$T_{round\text{-}trip}$	Round-trip cycle time for a concrete transport vehicle	h
t_{load}	Loading time	min
t_{unload}	Unloading time	min
L_{inner}	Distance inside the tunnel, from the portal to the worksite	km
L_{outer}	Distance outside the tunnel, from the portal to the concrete mixing station	km
V_{inner}	Average speed inside the tunnel	km/h
V_{outer}	Average speed outside the tunnel	km/h

D_{range}	Driving range of the electric concrete transport vehicle	km
$R_{round\text{-}trip}$	The maximum number of round trips each vehicle can make based on its driving range	/