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Dynamic Assessment of a Tunnel Overhead Contact System with Elastic Arm Support

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Abstract

Tunnel electrification systems employing elastic support arms offer an effective solution for maintaining a suitable pantograph–catenary interaction under restricted clearance conditions. This paper presents a dynamic assessment of a tunnel overhead contact system (OCS) inserted within a conventional flexible catenary through dedicated transition zones. The tunnel section employs twin contact wires supported by elastic arms supports, enabling compatibility with the surrounding electrification infrastructure while accommodating the geometric constraints imposed by tunnel environments. System performance is evaluated through numerical pantograph–catenary interaction simulations in accordance with standard assessment criteria, including mean contact force, standard deviation of contact force, and maximum contact force. The results indicate stable current collection behaviour over the entire operating speed range considered, from 80 to 160 km/h, with all force-related performance indicators remaining within the prescribed acceptance limits. These findings demonstrate the suitability of tunnel electrification systems based on elastic support arms for railway operations up to 160 km/h. Furthermore, the proposed modelling and simulation methodology proved effective for evaluating the dynamic performance of this electrification concept, providing a robust framework for future tunnel electrification projects and design optimisation studies.

Keywords: railway, catenary, pantograph, tunnel, electrification, dynamic analysis.

1 Introduction

Railway tunnel electrification for electric traction systems presents unique engineering challenges due to restricted clearances, installation constraints, and the need to maintain reliable current collection under a wide range of operating conditions. Unlike conventional open-track installations, tunnel overhead contact systems (OCS) often require dedicated support arrangements and transition structures that modify the mechanical characteristics of the electrification system. Consequently, the dynamic interaction between the pantograph and the OCS becomes a critical aspect of the design process.

Numerical simulation techniques have enabled detailed assessments of railway electrification systems during the design phase [1]. By combining finite-element catenary models with validated pantograph representations, it is possible to evaluate current collection quality before construction, identify critical infrastructure locations, and assess compliance with interoperability requirements.

To address the challenges associated with limited clearances, structural restrictions, and the transition between open-track and tunnel environments, dedicated OCS solutions must be adopted. Several alternatives are available, including rigid conductor rail systems [2] and flexible catenary-based arrangements, each offering distinct advantages and limitations. These differences affect not only current collection performance but also maintenance requirements, installation complexity, lifecycle costs, and the degree of integration with the conventional electrification system outside the tunnel. Therefore, the selection of a tunnel electrification solution must consider both cost, operational performance and adjacent infrastructure-related aspects.

The present work investigates an alternative tunnel OCS concept based on elastic support arms, as illustrated in Figure 1. The proposed system consists of twin contact wires supported by elastic arm structures, connected to a conventional flexible catenary through dedicated transition sections. At the transition, one of the contact wires is mechanically and electrically spliced with the messenger wire of the adjacent catenary, providing a gradual change in structural stiffness and current collection conditions. This arrangement offers an attractive solution for the electrification of single-track tunnels with strict clearance requirements.

Dynamic pantograph–catenary simulations are performed under representative railway operating conditions to evaluate current collection quality and compliance with interoperability requirements. The study aims to assess the dynamic performance of the proposed tunnel electrification concept and demonstrate its suitability for operation at speeds up to 160 km/h, while providing guidance for the design and optimisation of future tunnel electrification projects.

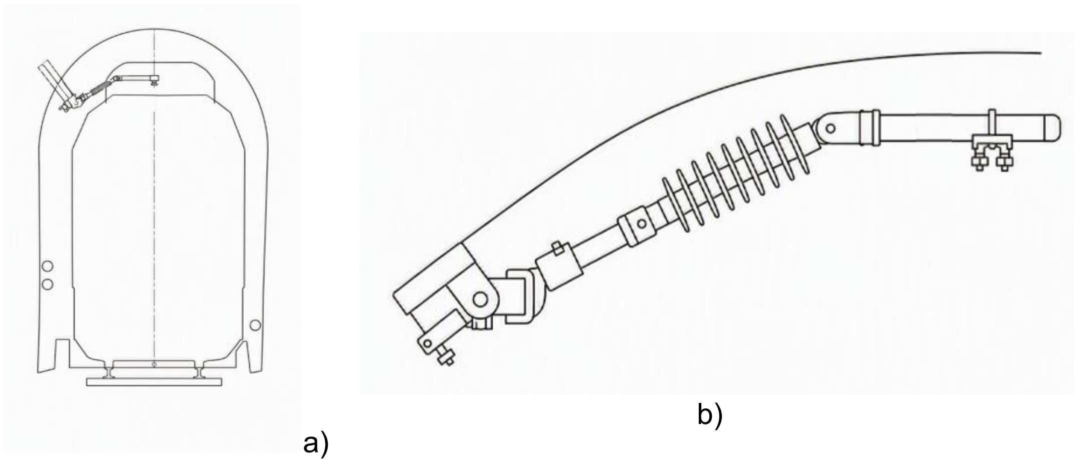

Figure 1: Representative tunnel overhead contact system employing elastic support arms: a) tunnel cross-section; b) detail view of the elastic support assembly.

2 Methods

The study is conducted using a detailed numerical model representing a complete installation of the tunnel OCL system integrated within a conventional, simple type, flexible catenary system. To this end, PantoCat software package [3] is employed to model the complete OCS and perform the dynamic simulations. The catenary models were developed using a finite-element discretisation capable of reproducing both the static equilibrium configuration and the propagation of dynamic disturbances generated by pantograph passage. Particular attention was devoted to the representation of the transition zones, as these regions combine structural and geometric discontinuities that significantly influence the dynamic response.

The finite-element model constructed is composed of three wire runs. The first and last wire runs are composed of two simple flexible catenaries representative of conventional speed operation, while the central wire run incorporated the tunnel OCL system and constitutes the main focus of this work. Illustrations of the finite-element model are presented in Figures 2 to 5.

The tunnel section is located at the centre of the middle wire run, where two contact wires are supported by elastic arm assemblies [4], discretised using finite elements. Note that this assembly provides an elastic support to the twin contact wires through a torsional spring located at the heel joint of the assembly, adjacent to the tunnel wall support. These elastic supports are distributed along the tunnel length, approximately every 15m, and designed to accommodate the geometric constraints associated with underground infrastructure.

Within the central wire run, immediately after the overlap section, the conventional OCL transitions towards the tunnel installation through the gradual introduction of a vertical gradient in both the messenger and contact wires, allowing the contact wire height to be adjusted to the reduced tunnel clearance. Subsequently, the final transition to the elastic support assemblies is set by three bespoke support consoles. Between the first and second consoles, the separation between the messenger wire and the contact wire is progressively reduced, while the messenger wire is spliced to a secondary contact wire that continues into the tunnel section. Between the second and third consoles, the secondary contact wire is gradually lowered until it reaches the same height as the main contact wire. Once both contact wires are aligned at the third console, the next wire supports are provided by the elastic arm assemblies throughout the tunnel section. At the tunnel exit, the same arrangement is implemented in reverse.

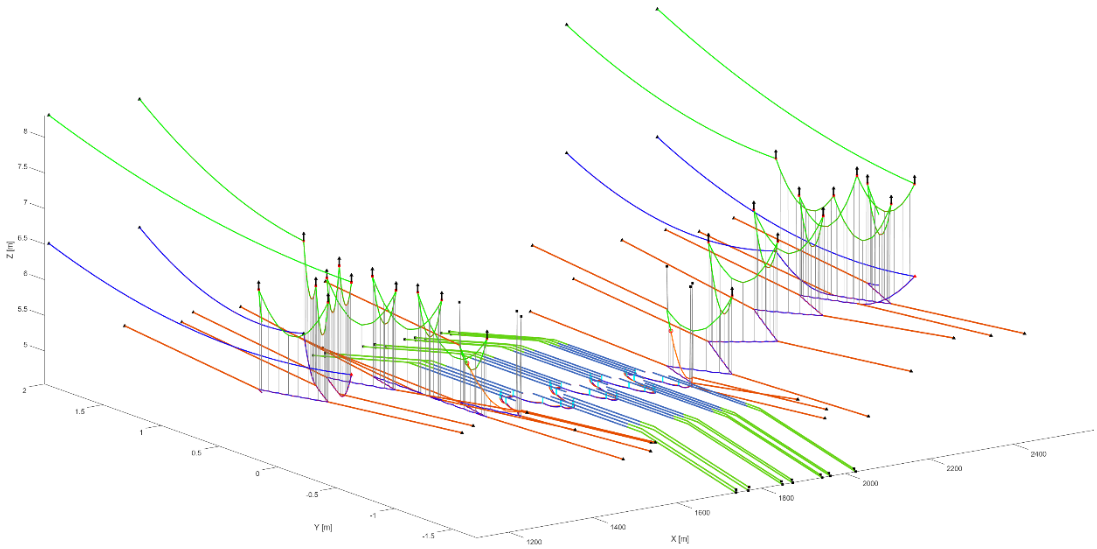

Figure 2: Perspective view of the tunnel OCL system.

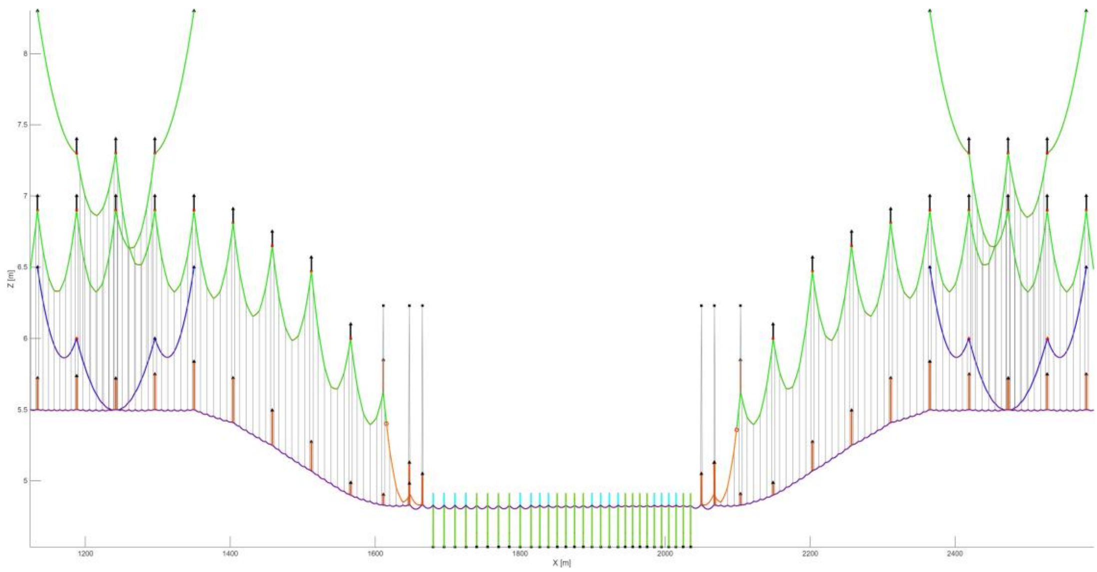

Figure 3: Lateral view of the tunnel OCL system.

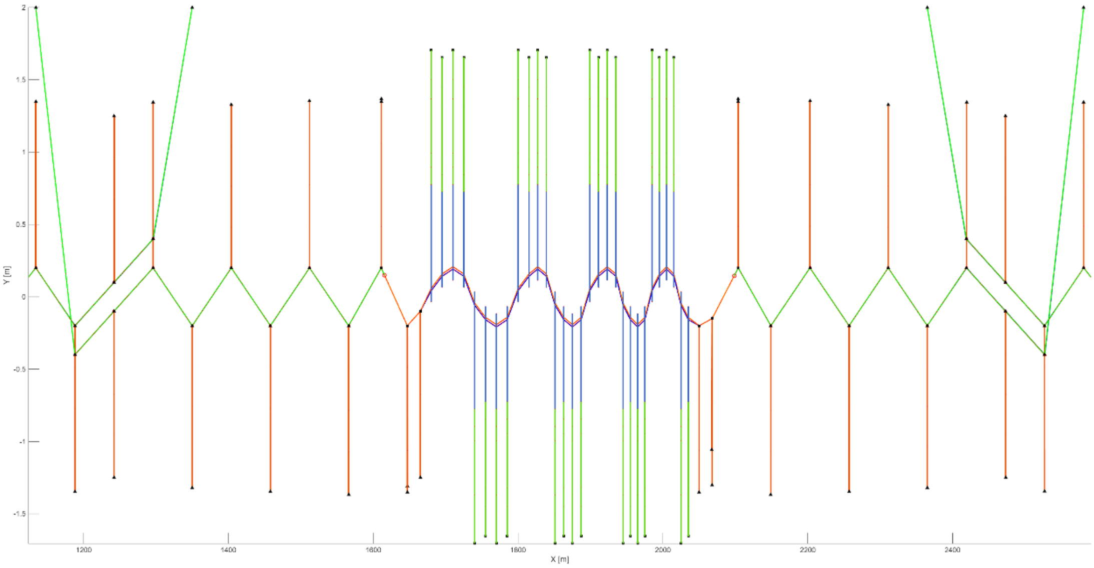

Figure 4: Top view of the tunnel OCL system.

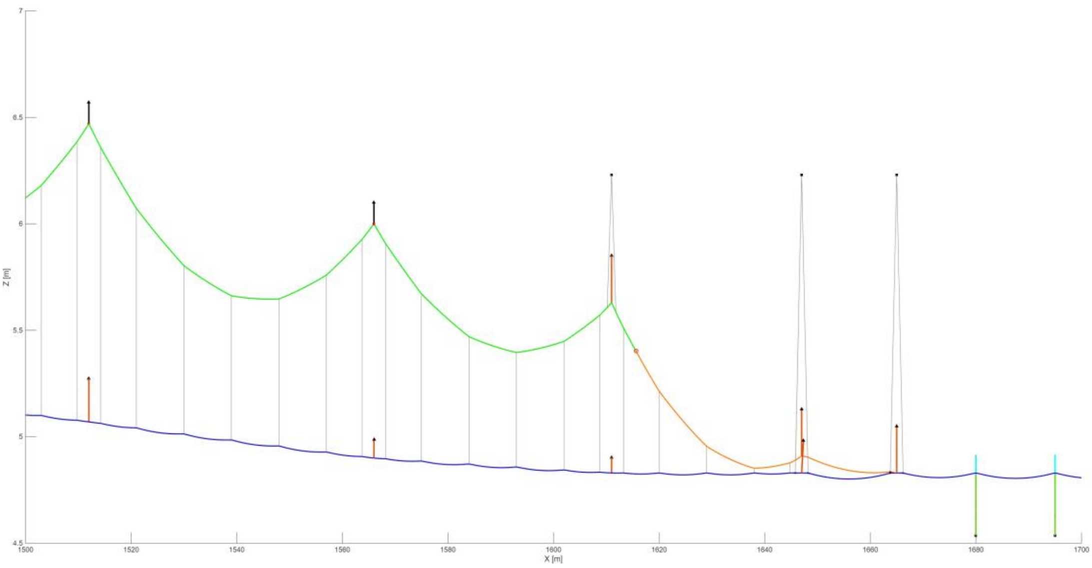

Figure 5: Side view of OCL transition zone.

3 Results

Assessment of the tunnel OCS system described in the previous section is performed through a series of simulation scenarios in which the OCS model is coupled with a suitable lumped-mass pantograph representation operating at different speeds and pantograph spacings. The present paper focuses on the results obtained for a two-pantograph configuration with a separation distance of 85 m. Operating speeds between 80 km/h and 160 km/h are considered. The analysis domain comprises the tunnel section and the adjacent entrance and exit transition regions, where the largest dynamic effects are anticipated.

Figure 6 presents the statistical parameters of the evaluated contact forces for the different operating speeds. The results indicate stable and consistent current collection behaviour throughout the investigated speed range. Mean contact forces remain centred within the admissible corridor defined by EN 50367, while the corresponding standard deviations remain significantly below the prescribed limits. No contact losses are observed.

Figure 7 presents the contact force histories obtained along the tunnel system and its transition regions for an operating speed of 160 km/h. Maximum and minimum contact forces occur within the transition regions located immediately before the tunnel entrance and exit. These locations coincide with changes in structural stiffness and contact-wire gradients, generating the highest levels of dynamic excitation. Nevertheless, all force-related performance indicators satisfy the interoperability requirements.

The simulations confirm that the transition regions govern a significant portion of the dynamic response of the system. Local variations in stiffness and geometry influence the evolution of contact forces and support reactions, making these regions particularly relevant during the layout design process.

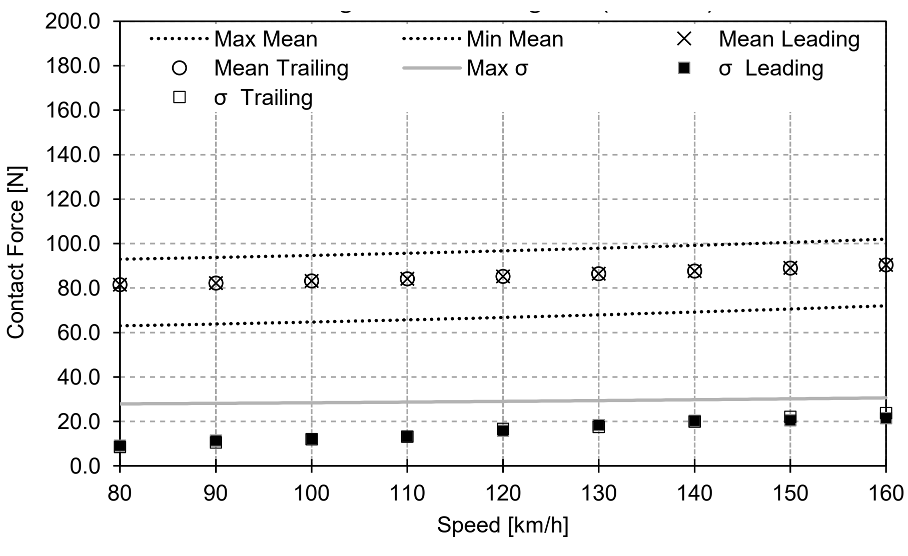

Figure 6: Contact force statistical parameters for 80 to 160 km/h speed range.

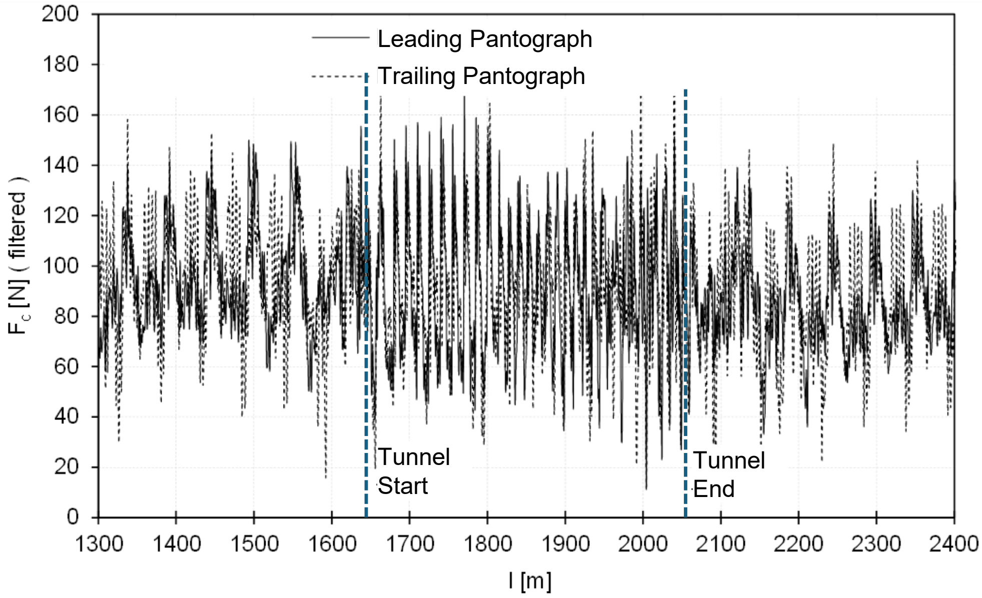

Figure 7: Evaluated contact force along the analysis region at 160 km/h.

4 Conclusions and Contributions

A numerical assessment of a tunnel overhead contact line (OCL) system based on elastic support arms has been presented. The study employed a coupled pantograph–catenary modelling approach that combines a finite-element representation of the OCL with a lumped-mass pantograph model to evaluate the dynamic interaction under representative railway operating conditions.

The results indicate that tunnel electrification systems based on elastic support arrangements are well suited to provide reliable current collection performance throughout the investigated speed range, from 80 to 160 km/h. All evaluated contact-force indicators remained within the prescribed acceptance limits, demonstrating the capability of the proposed concept to support railway operations at speeds up to 160 km/h.

The analysis also highlighted the importance of the transition regions between the conventional catenary and the tunnel electrification system. These sections were found to govern the most demanding dynamic responses and therefore require particular attention during the design, optimisation, and validation stages of the infrastructure development process.

The proposed numerical methodology was found to be an effective tool for assessing the dynamic behaviour of tunnel electrification systems and provides a robust framework for the comparison and evaluation of alternative designs. The approach can be readily extended to different infrastructure configurations, vehicle types, and operational scenarios.

Future work will focus on the investigation of curved-track installations, alternative tunnel geometries, and a more detailed analysis of the dynamic behaviour of transition regions, with the aim of further improving the performance and robustness of tunnel electrification systems.

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