Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 2.11
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.2.11

Supporting Railway Electrification with Novel Pantograph-Catenary Dynamic Analysis Tools

P. Antunes[1,2], J. Rebelo[1], J. P. Santos[1], J. Pombo[1,2,3], T. Kemp[4] and M. Whittaker[4]

[1]Institute of Railway Research, School of Computing and Engineering, University of Huddersfield, UK
[2]IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[3]ISEL, Instituto Politécnico de Lisboa, Portugal
[4]NR, Network Rail, United Kingdom

Abstract

The race for lower carbon emissions pressures railway transportation to meet demanding electrification goals. Infrastructure managers seek ways to electrify their network at an accelerated pace, challenging the industry for a faster, cheaper and less disruptive electrification. Conversely, rolling stock manufacturers carry the heft on providing an interoperable train-pantograph configuration able to perform through different parts of the network with different catenary designs. In this fast paced and complex environment, set to meet strict electrification goals, the industry seeks the employment of pantograph-catenary interaction dynamic analysis tools to validate and verify their design solutions at an accelerated pace, as well as provide a degree of assurance to the network. In this work, a novel pantograph-catenary modelling and dynamic analysis framework is proposed to respond to the industry demands, where these types of tools are able to be employed in an electrification project environment, helping to accelerate and ensure design and construction decisions. The use of such framework enables catenary systems to be automatically modelled following track geometry and the catenary design layouts provided as input. This includes the consideration of catenary systems with complex discrete features, set in in any arbitrary track geometry, such as curves and line junctions.

Keywords: railways, pantograph-catenary, overhead contact line, numerical analysis, dynamic analysis, numerical tools, electrification.

1 Introduction

Railway transportation plays a key role in worldwide transportation. The present demand for sustainable and green transportation puts in a challenge for railway transport decarbonization. In addition, as globalization and economic growth significantly increase, so does the demand for passenger and freight mobility. These effects have resulted in vast worldwide programs to remove from service diesel fleets and replace them by trains running on alternative power sources, in which rail electrification plays the main role.

Although railway electrification is a sustainable solution, it requires a significative starting capital investment. Thus, the railway industry is challenged in being able to carry a cost-effective accelerated electrification. The railway sector is also enquired to have versatile and interoperable rolling stock, capable to run in different networks. This raises difficulties in the authorization processes, required to ensure compliance on performance and safety standards. Here, the need to reduce or avoid expensive in line tests is also a key aspect challenged by the railway industry, which finds difficulty on introducing new technologies.

Recent developments on computational tools, able to study with detail pantograph-catenary dynamics, have been employed to better understand the interaction between these two systems [1]. Some of these tools have also been employed to reduce inline tests, such as in the case of European technical specifications for interoperability. The modernization of the railway industry and the maturity of these dynamic analysis tools has now put perspective on homologation procedures based on numerical simulations rather than on in-line measurements, which are very expensive and time consuming. However, it also has raised more challenges on the ability of this tools to be able to study and handle more complex problems. The industry seeks these tools to aid, accelerate and validate electrification projects, ensuring that the right engineering overhead line design decisions have been taken and avoiding risk on setting up complex electrified systems. This includes the electrification of current networks, as well as upgrading parts of older infrastructure to cope with increased traffic and operating speeds, while still planning for network expansion.

Pantograph–catenary interaction tools currently in use share key modelling approaches and have been successfully validated. A more restricted number of them have also been certified following EN50318:2018 [2]. Nevertheless, presently, most numerical tools available are limited to catenary models set in straight track and avoid complexities found in current electrification projects. The study of more complex problems, such as the ones set on a realistic electrification project, require advancements in the capabilities of these software. In this work, the most recent advancements implemented in *PantoCat* [3] are presented, addressing critical aspects to be accounted when considering the analysis of complex current collection systems. This includes the development of a pantograph-catenary dynamic analysis framework which enables the industry to employ these type tools in an electrification project environment.

2 A Pantograph-Catenary Dynamic Analysis Framework

The dynamic analysis tool here presented follows an integrated framework environment, established between different modules as depicted in Figure 1. A track geometry processing tool is able to build a moving reference frame of a track through geometric reconstruction, using track geometry parameters such as the curvature, cant and elevation. Hence, the position and spatial orientation of the track can be obtained at any track position and be fed to following modules.

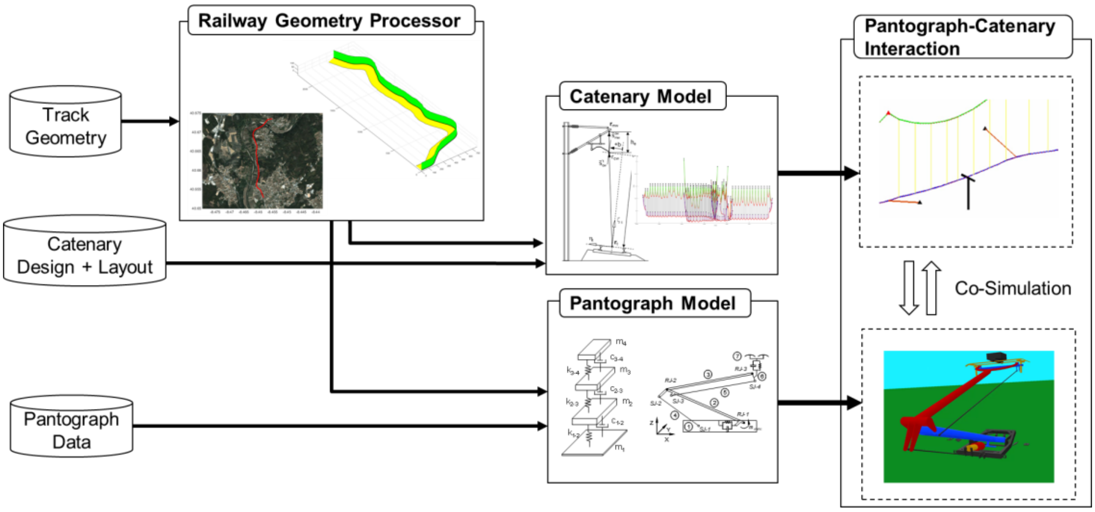

Figure 1: Dynamic analysis tool framework.

Several track geometries can be stacked in cases where the catenary system is set in multiple tracks. The catenary module is able to build a catenary finite element model of the whole overhead line system to be considered, according to additional catenary design data which are parametrized along the track length. The pantograph module is also able to employ the railway geometry database to set the spatial path of the pantograph along the track, or in other cases a secondary database can be provided to include vehicle movements and oscillations. A co-simulation module couples the dynamic effects between the generated catenary and pantograph models, to analyze its interaction in the time domain. Note that this framework scheme effectively separates the analysis tool into several modules. These modules can be used independently for particular types of analyses, as necessary. It also enables each of the sub-systems to be numerically modelled with a mathematical formulation that is best suited for each case. *PantoCat* modular architecture has the advantage of allowing each module to run independently, providing a unique development platform where each module can be developed individually, its capabilities are also extended and as they can be employed for different types of analysis.

3 Methodologies

In general, the development of pantograph-catenary dynamic analysis tools is a multidisciplinary exercise. *PantoCat* uses the Finite Element (FE) methodology [4] to study the catenary and the multibody formulation [5] to represent the pantograph [6].

These two heterogenous formulations are integrated via an efficient co-simulation environment [7]. Both sub-models are bridged through a contact model which employs a penalty formulation. Presently, *PantoCat* is extensively used in research and consultancy projects for the rail industry, being certified by an independent notified body to EN50318:2018 standard [2]. It is a fully three-dimensional (3D) tool, capable of modelling rigid and flexible catenaries with multiple sections, including overlaps [8] and gradients. Multiple pantograph operation can be considered [9], as well as other complex loads on the components, including aerodynamic effects [10], [11]. A geometric reconstruction algorithm, [12], enables a geometry pre-processor to be able to spatially define the position of all the catenary model finite element nodes and elements according to track data, such as curvature, cant and elevation. To this effect, the geometry pre-processor establishes a moving frame of reference as a function of the track travel length [13]. As catenary design layouts are set according to the track length and its geometric parameters are set in reference to the track surface, it is possible to establish a spatial position for any key point of the catenary design. Hence, dynamic studies in tangent or curved tracks, [14], can be considered as well as additional irregularities and perturbations [15].

The pantograph can be modelled either as staged spring-damper lumped mass system or as a 3D multibody model. The former is a linear representation of the pantograph, where model parameters are identified experimentally to match the same frequency response of the pantograph. Although these models reproduce with fidelity the dynamic response of the real pantograph, the identified parameters have no physical realism and the model validity is limited to the test setup parameters such as working height. The multibody model approach is also implemented in *PantoCat* with the aim to provide a better physical representation of the pantograph, including its nonlinear behaviour.

4 A Realistic Case Scenario on Electrification

The advanced features here detailed allow for the simulation of sophisticated and detailed models of the pantograph and catenary models containing large sets of data. The set of output data includes not only the pantograph-catenary contact forces but also all the kinematics of each mechanical element of the pantograph and catenary, and the internal forces on both systems.

This computational tool is able to analyse pantograph–catenary dynamic interaction in realistic operating conditions. The catenary and pantograph sub-models address complete overhead energy collecting systems that include all mechanical details of the pantograph components and the complete topology and structural details of the catenary [16], [17], [18]. These advancements are portrayed in Figures 2 and 3, where this tool as been employed in the overhead line design of a real electrification project. The project in question involved the electrification a railway junction, depicted in Figure 2. The junction presents a series of design constraints for which standard design approaches required a heavy and unacceptable operating speed reduction. The use of the dynamic analysis tool permitted overhead line design engineers to access the dynamic behavior of the system and propose several innovative design variations.

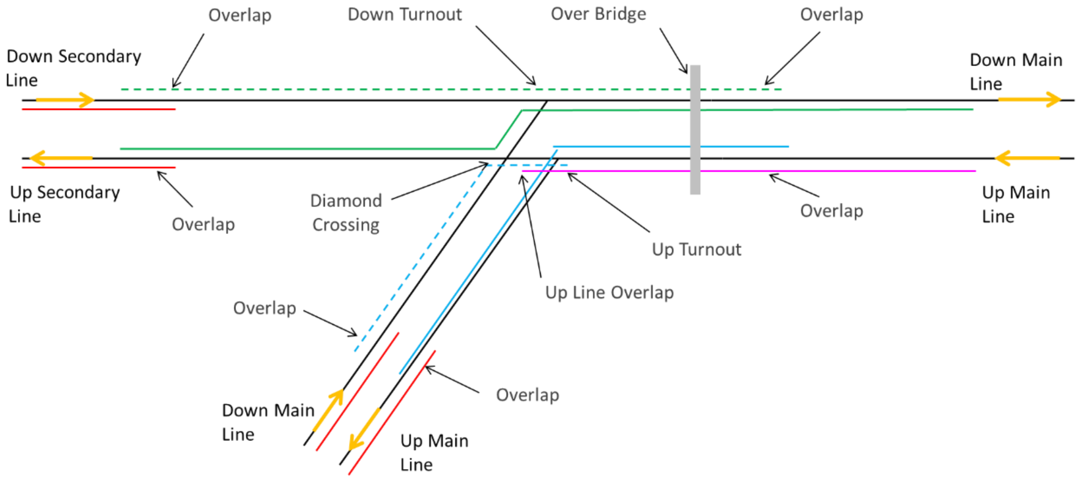

Figure 2: Overhead contact line layout at a railway.

Figure 3 presents the model of one of these design variations, this is a finite element model of a comprehensive catenary system installation regarding a junction of four railway tracks merging into two. The model considers the position of all components according to the track geometry and catenary layout designs provided. It also accounts for gradients and an under bridge.

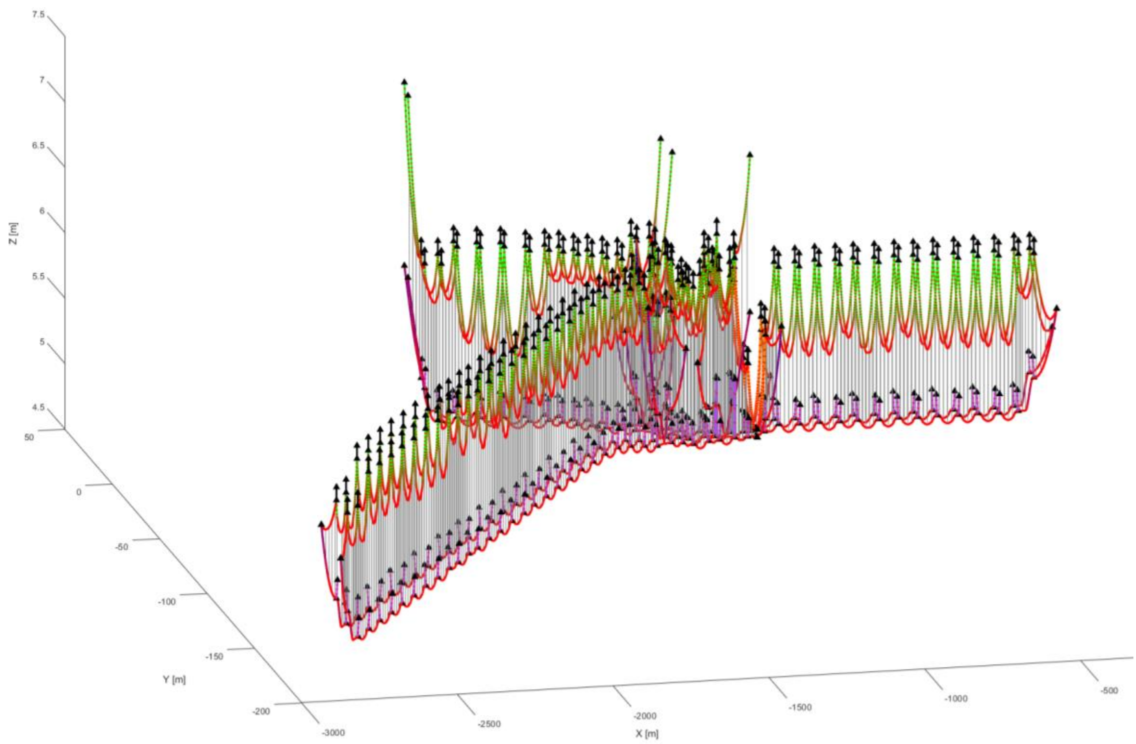

Figure 3: Model of a catenary system set at a railway junction.

Several design options were able to be considered in an iterative process, where at each pass a new catenary model was generated and the corresponding pantograph-catenary simulation results analyzed. Each of these steps permitted engineers to better understand the dynamic behavior of the system and identify critical design aspects, which in turn were re-designed and re-evaluated until an appropriate design solution was found

4 Conclusions and Contributions

The outcome of the work here detailed presents the development of a robust pantograph-catenary dynamic analysis tool able tackle more complex features. An additional set of modelling methodologies and the development of an integrated framework enables a pantograph-catenary analysis tool, PantoCat, to extend its capabilities and be able to handle more complex problems in response to the most recent industry challenges on electrification. Overhead line infrastructure managers or designers and rolling stock manufactures are able to employ this tool to validate, plan and analyse their technical solutions. This promotes a more efficient and effective electrification at a lower cost, where design solutions can be analysed and de-risked in an accelerated design environment. In general, most dynamic analysis tools are limited to catenary models set in a single straight track. The developed framework aims to enhance an already developed tool to be capable of dealing with catenary models set in arbitrary track geometries and in multiple lines. It also enables the tool to account for more critical realistic cases such as line junctions, crossovers, gradients and overbridges, among others. In addition to the more common lumped mass pantographs models that retain a strict set of modelling considerations and model validity, this tool is also able to consider novel multibody pantograph models. The set of additional capabilities provided by these developments aim to support the railway industry in adding capability to tackle the demand for accelerated and cost-efficient electrification.

Acknowledgements

The authors gratefully acknowledge Fundação para a Ciência e a Tecnologia (FCT) for its financial support via the project LAETA Base Funding (DOI: 10.54499/UIDB/50022/2020).

References

[1] S. Bruni *et al.*, “The results of the pantograph–catenary interaction benchmark,” *Vehicle System Dynamics*, vol. 53, no. 3, pp. 412–435, Mar. 2015, doi: 10.1080/00423114.2014.953183.

[2] “EN 50318:2018 - Railway applications - Current collection systems - Validation of simulation of the dynamic interaction between pantograph and overhead contact line,” 2018, *CENLEC*.

[3] J. Ambrósio, J. Pombo, P. Antunes, and M. Pereira, “PantoCat statement of method,” *Vehicle System Dynamics*, vol. 53, no. 3, pp. 314–328, Mar. 2015, doi: 10.1080/00423114.2014.969283.

[4] K.-J. Bathe, *Finite Element Procedures*, 2nd ed. K.J. Bathe, Watertown, MA, 2014.
[5] P. E. Nikravesh, *Computer-Aided Analysis of Mechanical Systems*. Englewood Cliffs, New Jersey: Prentice-Hall, 1988.
[6] J. Pombo and J. Ambrósio, “Influence of pantograph suspension characteristics on the contact quality with the catenary for high speed trains,” *Comput Struct*, vol. 110–111, pp. 32–42, Nov. 2012, doi: 10.1016/j.compstruc.2012.06.005.
[7] P. Antunes, J. Ambrósio, J. Pombo, and A. Facchinetti, “A new methodology to study the pantograph – catenary dynamics in curved railway tracks,” *Vehicle System Dynamics*, vol. 3114, 2019, doi: 10.1080/00423114.2019.1583348.
[8] P. Antunes, J. Ambrósio, J. Pombo, and M. Pereira, “Dynamic Analysis of the Pantograph-Catenary Interaction on Overlap Sections for High-Speed Railway Operations,” in *Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance*, Stirlingshire, UK: Civil-Comp Press, 2014. doi: 10.4203/ccp.104.142.
[9] J. Pombo and P. Antunes, “A Comparative Study Between Two Pantographs In Multiple Pantograph High-Speed Operations,” *Internatinal Journal of Railway Technology*, vol. 2, no. 1, pp. 83–108, 2013, doi: 10.4203/ijrt.2.1.4.
[10] J. Pombo and J. Ambrósio, “Environmental and track perturbations on multiple pantograph interaction with catenaries in high-speed trains,” *Comput Struct*, vol. 124, no. October, pp. 88–101, Aug. 2013, doi: 10.1016/j.compstruc.2013.01.015.
[11] J. Pombo, J. Ambrósio, M. Pereira, F. Rauter, A. Collina, and A. Facchinetti, “Influence of the aerodynamic forces on the pantograph–catenary system for high-speed trains,” *Vehicle System Dynamics*, vol. 47, no. 11, pp. 1327–1347, Nov. 2009, doi: 10.1080/00423110802613402.
[12] W. C. Iverson, “Analysis of the Reconstruction of Rail Geometry from Curvature Data,” *IEEE Trans Ind Appl*, vol. IA-10, no. No. 3, pp. 368–379, May 1974, doi: 10.1109/TIA.1974.349163.
[13] J. Ambrósio, P. Antunes, and J. Pombo, “On the Requirements of Interpolating Polynomials for Path Motion Constraints,” in *Mechanisms and Machine Science*, vol. 26, A. Kecskeméthy and F. Geu Flores, Eds., Springer International Publishing, 2015, pp. 179–197. doi: 10.1007/978-3-319-10723-3_19.
[14] P. Antunes, J. Ambrósio, J. Pombo, and A. Facchinetti, “A new methodology to study the pantograph–catenary dynamics in curved railway tracks,” *Vehicle System Dynamics*, vol. 58, no. 3, pp. 425–452, Mar. 2020, doi: 10.1080/00423114.2019.1583348.
[15] Y. Song, P. Antunes, J. Pombo, and Z. Liu, “A methodology to study high-speed pantograph-catenary interaction with realistic contact wire irregularities,” *Mech Mach Theory*, vol. 152, p. 103940, Oct. 2020, doi: 10.1016/j.mechmachtheory.2020.103940.
[16] J. Ambrósio, J. Pombo, M. Pereira, P. Antunes, and A. Mósca, “Recent developments in pantograph-catenary interaction modelling and analysis,”

International Journal of Railway Technology, vol. 1, no. 1, pp. 249–278, 2012, doi: 10.4203/ijrt.1.1.12.

[17] P. Antunes, A. Mósca, J. Ambrósio, J. Pombo, and M. Pereira, “Development of a Computational Tool for the Dynamic Analysis of the Pantograph-Catenary Interaction for High-Speed Trains,” in *Civil-Comp Proceedings*, 2012, pp. 1–25. doi: 10.4203/ccp.99.129.

[18] J. Ambrósio, J. Pombo, P. Antunes, and M. Pereira, “PantoCat statement of method,” *Vehicle System Dynamics*, vol. 53, no. 3, pp. 314–328, Mar. 2015, doi: 10.1080/00423114.2014.969283.