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Systematic Mapping of Numerical Models and Methods for Pantograph-Overhead Conductor Rail Interaction Using PRISMA Method

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Abstract

Numerical simulations of the pantograph and overhead conductor rail (OCR) dynamic interaction are widely used to evaluate contact quality and assessing effects on current collection, wear and components. This study systematically maps numerical modeling approaches and evaluation measures for pantograph-OCR dynamics, following the PRISMA methodology. Searches in Scopus, Web of Science, and IEEE Xplore yielded 259 publications, of which 41 were analyzed in detail.

The OCR is mainly modeled using beam-based formulations using finite element discretization or global shape-function superposition. Discrete components such as supports are typically represented as equivalent spring-mass systems. Pantographs are most often modeled as lumped-mass systems, followed by multi-body formulations, while fully-flexible finite element models are rare. Contact is predominantly treated using penalty methods. Many studies omit key numerical parameters, such as time step or element length.

Main elements and measures, concerning the dynamic contact force, have been identified in the publications and compiled in a comprehensive overview. Most studies focus on parameter variations, such as train speed, span length, and geometry or material properties. Wear-related phenomena emerge as a major research theme.

Keywords: review, PRISMA, systematic mapping, overhead conductor rail, rigid catenary, pantograph, simulation, contact force, numerical methods

1 Introduction

The interaction between the pantograph and the overhead contact system (OCS) in the railway domain has been studied for some time. While the interaction between pantographs and elastic overhead contact lines (OCL) has been thoroughly investigated, the interaction between pantographs and rigid overhead conductor rails (OCR) has only attracted significant attention in recent years. Compared with the OCL, the OCR has advantages like small installation space, which makes it very suitable for tunnels, less maintenance and greater electrical capabilities. On the other hand, the challenge lies in the high stiffness and weight of the system. This results in the need to install supports at close distances, since small unevenness in the OCR has great impact on the pantograph. To manage contact force fluctuations and abnormal wear at high speed, detailed simulations are necessary. The OCR has been mentioned in past reviews that focus on OCLs [1–4]. No review solely focuses on the topic of OCR, thus the creation of this systematic mapping is well motivated. [5–12]

Given the existing publications on the topic of pantograph-OCR interaction, some build on each other while others are developed independently. Hence, the objective of this systematic mapping is to give an overview of the methods used to describe different aspects of the numerical system and to identify which elements have been investigated and what measures have been used to do so, in order to assess what capabilities a simulation tool might need. This overview can be used as a starting point and subsequent development for researchers in this field. Thus, the objectives of this systematic mapping are summarized in the following questions:

- Which models are used to simulate the dynamic behavior between pantograph and the OCR?
- Which elements are mainly investigated in the dynamic simulations and what measures are used?

To get an understanding of the concept of the pantograph-OCR interaction, the investigated components are briefly described. The pantograph is a current collection device placed on top of the train's roof. Due to its design, it is able to oscillate in mostly vertical direction. A force is applied at the mechanism's bottom to push the pantograph current collector strips to the OCR to ensure stable contact. The OCR is connected to the power grid to supply the train's electrical system with energy through the pantograph. Thus, contact quality is of great importance for train operation, which is mostly described by the contact force (CF). Because of its complex dynamic effects, simulation tools are usually used for assessing the CF. Different elements of the OCR need to be considered in the simulation. The main part is the rigid rail consisting of a profile beam-like structure, that clamps a contact wire at its bottom, which in turn is in contact with the pantograph. Besides that, there are systems without a separate contact wire [9]. As the linear density of the rail is quite high, it needs supports at regular close intervals (6 to 12 m) to secure the rail to the environment. To seamlessly connect the individual rails at their front ends to form a long rail, bolts are used in the connecting mechanisms provided. Every 250 to 500 m a transition is needed to account for thermal expansion effects. If needed, the transition from OCL to OCR also needs to be considered. [5–12]

The remaining content of this paper is divided into the following parts. The selection process of publications, following the PRISMA method, is stated in the following Sect. 2. Subsequently, the first research question concerning the numerical methods is evaluated in Sect. 3. Lastly, the second research question concerning the mainly investigated elements and measures is presented in Sect. 4. At the very end this paper closes with the conclusion 5.

2 PRISMA Methodology

This systematic mapping was performed based on the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) [13]. Records were searched in the Scopus, Web of Science and IEEE Xplore databases utilizing the following queries:

- In Scopus:
  TITLE-ABS-KEY((“rigid catenary” OR “overhead conductor rail” OR “rigid overhead” OR “rigid conductor” OR “rigid-conductor”) AND (simulat* OR model* OR dynamic* OR numeric* OR comput* OR interact* OR validat* OR sensitiv* OR influenc*))
- In Web of Science:
  Topic:(”rigid catenary” OR ”overhead conductor rail” OR ”rigid overhead” OR ”rigid conductor” OR ”rigid-conductor”) AND Topic:(simulat* OR model* OR dynamic* OR numeric* OR comput* OR interact* OR validat* OR sensitiv* OR influenc*)
- In IEEE Xplore:
  ((”rigid catenary” OR ”overhead conductor rail” OR ”rigid overhead” OR ”rigid conductor” OR ”rigid-conductor”) AND (simulat* OR model* OR dynamic* OR numeric* OR comput* OR interact* OR validat* OR sensitiv* OR influenc*))

The records had to fulfill the following eligibility criteria in order to be included in the analysis. Only articles, full conference papers, reviews and books or book chapters in English language were considered. Moreover, the publications must address OCRs and include numerical modeling of the pantograph and OCR system aswell as the computation of the dynamic contact force between pantograph and the contact wire. The search was performed on 15 January 2026.

Figure 1 depicts the applied selection process based on the PRISMA statement. The search yielded a total of 259 records, of which 169 were found in Scopus, 72 in Web of Science and 18 in IEEE Xplore. 71 of the found records were removed as duplicates in the *identification* phase. In the subsequent *screening* phase, titles and abstracts of the remaining records were perused, excluding 101 records that cleary did not meet the defined eligibility criteria, mostly because of the topic not being OCR and the publication being written in another language than english. The remaining 87 reports were sought for retrieval, whereby 24 could not be retrieved because of restricted online access. The full texts of the remaining 63 reports were downloaded as pdf documents, saved in the commercial reference management software Citavi, and assessed for eligibility by analyzing their full texts. 3 reports were excluded because of not being the requested publication type (paper/journal/book), 1 report was not about OCRs and 18 reports had no dynamic CF simulation aspect. A final set of 41 reports was *included* in the following analysis.

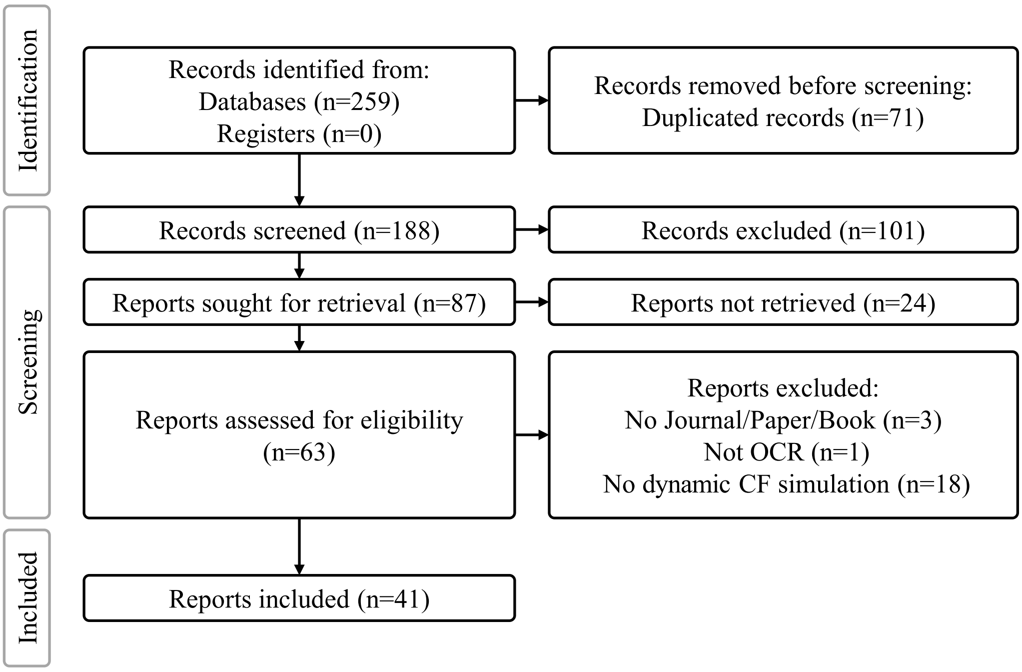

Figure 1: Flow chart of study selection process (adapted from the template in [13])

3 Numerical Modeling

Numerical modeling is essential for assessing the dynamic contact quality between the pantograph and the OCR. Various modeling approaches have been proposed for different subsystems. These approaches are reviewed and presented in the following sections. If a publication is not cited for a particular subsystem, the corresponding subsystem is either not considered or its treatment is not clearly specified in the publication.

3.1 Rigid Catenary

The rail, consisting of the aluminium profile and contact wire, is modeled in all publications as a single body, since the clamping force is high enough to prevent relative motion. Accordingly, equivalent properties for linear density, bending stiffness and tensile stiffness are computed to account for the composition of both cross sections. Equations for this simplficiation are given, e.g. in [7], or can be retrieved using commercial FE software. The rail is modeled in most publications as some kind of beam to capture its inertial and stiffness characteristics. The internal load assumptions depend on the selected beam theory. The most widely used options are the Euler-Bernoulli beam [5, 7, 11, 14–23] and Timoshenko beam [6, 10, 24–31]. Other beam types consider similar load cases, such as the "space-beam" in [8, 32] or specific beam elements related to commerical software like the ANSYS Beam188 element [33]. Beam modeling of the rail is predominantly performed using local discretization based on the FE method [5–8, 10, 12, 14–17, 21, 24–36] or utilizing superposition of global shape functions [18, 20, 22, 23, 37]. It should be noted that most publications do not give detailed information about the element lengths used. Maximum element lengths for FE models are given in [5] as 0.5 m, in [6, 24–26] as 0.2 m and in [34] as 0.01 m. A full 3D FE model for dynamic simulation is presented in [38]. Geometric nonlinearity is discussed in [16], where it is shown that linearization after static shape finding does not significantly affect the results of dynamic simulation while substantially reducing the computational cost.

Special cases consider the OCR as a vibrating plate [39] or as displacement based on a contour or harmonic excitation [9, 40, 41] or as a time varying stiffness in [42]. This results in computationally very efficient systems. Also noteworthy is [5], as here the calculated first eigenfrequencies and their corresponding eigenmodes of the OCR are transferred from ANSYS to SIMPACK in the form of the mass and stiffness matrix containing eigenbehavior.

Damping is found to be negligible in [5, 6]. However, one can conclude that damping properties become especially relevant when multiple pantographs are used [18, 26]. Most publications that include damping adopt a linear combination of the mass matrix $\boldsymbol{M}$ and stiffness matrix $\boldsymbol{K}$, scaled by the coefficients α and β, to construct the damping matrix $\boldsymbol{D}$ of the catenary system, as given in Eq. 1. This formulation, commonly referred to as Rayleigh Damping, is used in [7, 8, 10, 12, 17, 20, 22, 28–30].

$$\boldsymbol{D} = \alpha \boldsymbol{M} + \beta \boldsymbol{K} \tag{1}$$

The coefficients are chosen either in accordance to the European standard EN 50318 or calculated for the catenary at hand by chosing representatives modes and their damping ratios [7, 12, 17, 28]. As an alternative approach, modal damping is used in [5], employing experimentally determined damping ratios.

Moving on, discrete catenary components such as the joints connecting multiple rails, supports and transitions are considered. The joints are commonly modeled as lumped masses [8, 10, 30, 31] or as point elements with additional rotary inertia [6, 24–26]. While [5] claims that their influence is negligible and can be omitted, [12] demonstrates that they have a noticable effect on the CF.

Supports are almost always reduced to equivalent spring-mass-damper representations, with the stiffness values ranging from orders of 10^4 to 10^7 N/m [5, 7, 14, 24, 33]. Models employing only spring elements are used in [5–7, 12, 14, 24–26, 31–33]. Spring-mass representations are used in [8, 17–19, 22, 23, 30, 43, 44], while bar elements, which are closely related to spring-mass systems, are adopted in [15, 16, 34]. Spring-mass-damper elements are utilized in [10, 27, 29] and spring-damper elements in [37]. A full 3D FE model of the support structure is used in [38]. While many publications employ assumed stiffness values, in [24] the support stiffnesses are matched through modal validation with a real track.

The modeling of transition elements can be categorized into three types: overlapping spans, expansion joints, and elastic-rigid transitions. The first two represent transitions between rigid rails. Overlapping spans are modeled using two decoupled rails, with the pantograph allowed to interact with both simultaneously [7, 8, 45]. For the expansion joint, changed mechanical properties need to be considered, due to the different geometry. Also restricted degree of freedom (DoF) constraints need to be considered between the expansion-connecter and the new rail, allowing axial motion [8, 29, 45]. The model for the expansion joint in [45] also allows for misalignment in order to investigate the influence on the CF. Elastic-rigid transitions require explicit modeling of an elastic OCL. In [33], the transition element is represented by an additional beam fully constrained to the OCR, featuring stepwise reductions in cross section toward the OCL, with every slot connecting the OCL to the OCR.

3.2 Pantograph

The modeling of the pantograph can be classified into lumped-mass models [6–12, 14–19, 21–32, 34, 37, 40–43], multi body system (MBS) models [12, 20, 34, 35, 44, 46], full FE models [22, 36, 38] and a single spring-supported flexible beam model [39].

Lumped-mass models represent the pantograph as discrete point masses, restricted in vertical direction, connected by springs and dampers. In some studies additional force saturation elements are added [6, 24–26].

MBS typically use rigid or flexible bodies connected by joints, with some studies employing transfer matrices to describe dynamic response behavior [20]. Hard stops are also implemented in certain MBS models to limit motion and capture realistic contact conditions [5].

3.3 Contact Models

Different Contact Models have been used. The most prominent method is based on a stiffness connecting the two contact partners, commonly referred to as the penalty method [5–8, 11, 12, 15, 16, 18–21, 23–26, 28–32, 37, 42–44, 46]. The contact stiffness value is given as 50000 N/m in [5, 6, 8, 24–26, 32] and 82300 N/m in [20, 23, 42]. Some models also include damping in the contact [12, 20, 37, 43, 44, 46]. Only one explicit value is reported in [20] with a specific damping coefficient of 40 Ns/m. Alternative approaches include the Hertz contact theory [22, 46] and non-penetration methods such as the Lagrange multiplier method used in [14, 17].

Several specialized effects have also been considered. The contact surface area is explicitly modeled in [5, 14, 22] and contact effects in axial and transversal direction are incorporated in [35, 38]. Regardless of the specific contact formulation, all models account for the possibility of contact loss, which introduces nonlinearities and complicates numerical solution.

3.4 Solver

Several publications specify the numerical solvers used for dynamic simulations. The implicit Newmark-beta method is used in [15–18, 32], central differences in [7, 38], explicit Newmark in [20], Hilber-Hughes-Taylor in [34] and Runge-Kutta 4th order in [23]. Also commercial software has been used, which often rely on specialized internal solvers. This includes ANSYS [6, 22, 24–26, 33], ADAMS [43], SIMPACK [5] and Abaqus [38]

When the pantograph is modeled as an MBS, co-simulation techniques are applied. In [12], a Newmark solver is applied for the integration of the catenary system, while the pantograph MBS is solved using a fourth-order Runge-Kutta scheme. In [5], the modal behavior of the OCR system is exported from ANSYS to SIMPACK, allowing the entire system to be solved within SIMPACK.

Only few publications report the chosen integration time step. Values include 1 ms [17], 2.5 ms [6, 25, 26] and 5 ms [24]. In [7] it is noted that the maximum stable time step is determined by the element length divided by the wave propagation speed. However, a general guideline is not conclusive, as multiple wave types exist and bending-induced dispersion causes wave speed to vary with frequency.

In [7] it is emphasized that the system matrices can be pre-conditioned, exploiting properties such as symmetry and sparsity, which improves numerical efficiency.

4 Elements und Measures

The superordinate motivation across all reviewed publications can be summarized in increasing train speed and improving safety as well as reliability. In this chapter, it is investigated how these motivations are approached, considering the main elements examined in regards to dynamic simulation. *Contact Force* is chosen as an element when a main research focus is based on the CF itself, without considering specific individual elements. The main elements (on the right side) are linked to their measures (on the left side) used to investigate dynamic behavior in Fig. 2.

Regarding the main elements, 11 publications have a main research aspect that directly analyzes the CF, employing a wide range of measures. Furthermore, the pantograph and OCR elements appear to be of comparable research interest, as both are represented by a large number of publications within this categorization. The different measures indicate how the pantograph has been modified. Beyond these aspects, wear emerges as a particularly prominent topic addressed in 9 publications and associated with a broad set of measures. Overall, the measures most frequently investigated involve variations in train speed and span length. However, the literature as a whole covers a wide and diverse range of research topics.

5 Conclusion

Based on the PRISMA methodology, a total of 41 publications were selected and subsequently analyzed with respect to their modeling strategies, numerical implementations, and research objectives regarding dynamic CF calculation between pantographhcs and OCR.

Addressing the first research question, a state of the art of numerical modeling approaches is established. Most frameworks employ either finite element-based or global shape-function superposition methods considering beam formulations to represent the OCR. In specific cases, more detailed 3D FE models or simplified representations are adopted to address particular research questions. Damping effects are mostly integrated in the form of Rayleigh-Damping and sometimes assumed to be negligible. However, its influence is not systematically investigated. Pantographs are predominantly modeled using lumped-mass representations, although a substantial body of work applies MBS models. Fully flexible FE models of the pantograph are restricted to specialized studies. For contact modeling, the penalty method is clearly dominant, while non-penetration formulations are used less frequently. Approximately half of the reviewed publications explicitly state the numerical solver or commercial software employed, with ANSYS-based workflows and Newmark-type time integration schemes being particularly common. Nevertheless, crucial numerical details such as integration time step selection, element discretization length are reported only sporadically, limiting the reproducibility and comparability of results.

The second part of this work focused on the main elements considered and measures used in the publications, regarding dynamic CF calculations. These were consolidated in a comprehensive overview (Fig. 2). A large proportion of studies investigate the influence of parameter variations on the CF. This includes mainly train speed, span length, pantograph characteristics and OCR geometry and material properties. Wear-related phenomena constitute a major research focus and is connected to many

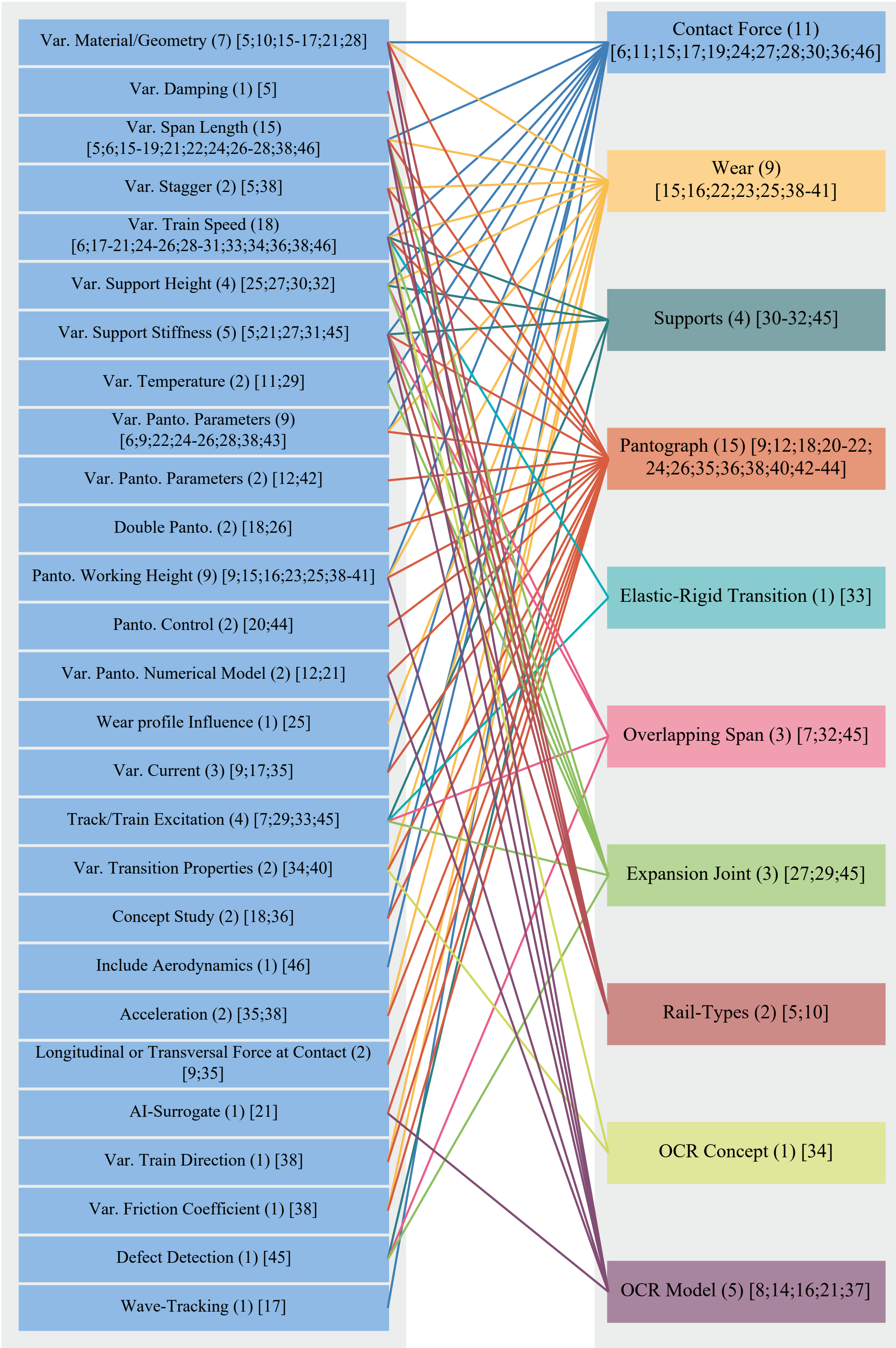

Figure 2: Overview of Measures (left) and main Elements (right) used in the publications with emphasize on dynamic simulation. (Var. = Variation, Panto. = Pantograph)

measures taken. Beyond these dominant themes, a wide range of additional topics is addressed, reflecting the diversity of research objectives within the field.

Based on the reviewed literature, several directions for future research can be identified. First, the role of damping, particularly in multi-pantograph configurations, requires more systematic investigation. Second, wear modeling would benefit from more detailed and application-specific prediction models tailored to particular infrastructure and operating conditions. Finally, transition zones, including rigid-rigid and elastic-rigid interfaces, deserve increased attention, as they have been shown to exert a pronounced influence on contact dynamics and system performance.

References

[1] S. Bruni, G. Bucca, M. Carnevale, A. Collina, and A. Facchinetti, "Pantograph–catenary interaction: Recent achievements and future research challenges," *International Journal of Rail Transportation*, vol. 6, no. 2, pp. 57–82, 2018. DOI: 10.1080/23248378.2017.1400156.

[2] Z. Liu, Y. Song, Y. Han, H. Wang, J. Zhang, and Z. Han, "Advances of research on high-speed railway catenary," *Journal of Modern Transportation*, vol. 26, no. 1, pp. 1–23, 2018. DOI: 10.1007/s40534-017-0148-4.

[3] G. Wu *et al.*, "Pantograph–catenary electrical contact system of high-speed railways: Recent progress, challenges, and outlooks," *Railway Engineering Science*, vol. 30, no. 4, pp. 437–467, 2022. DOI: 10.1007/s40534-022-00281-2.

[4] S. Bruni, G. Bucca, A. Facchinetti, S. Gregori, and J. Pombo, "Recent developments on pantograph-overhead line interaction," *Vehicle System Dynamics*, vol. 63, no. 7, pp. 1358–1394, 2025. DOI: 10.1080/00423114.2025.2484453.

[5] C. Vera, B. Suarez, J. Paulin, and P. Rodriguez, "Simulation model for the study of overhead rail current collector systems dynamics, focused on the design of a new conductor rail," *Vehicle System Dynamics*, vol. 44, no. 8, pp. 595–614, 2006. DOI: 10.1080/00423110500165499.

[6] M. Simarro, J. J. Castillo, J. A. Cabrera, and S. Postigo, "Evaluation of the influence of the speed, preload and span length on the contact forces in the interaction between the pantograph and the overhead conductor rail," *Engineering Structures*, vol. 243, 2021. DOI: 10.1016/j.engstruct.2021.112678.

[7] J. Benet, F. Cuartero, T. Rojo, P. Tendero, and E. Arias, "A dynamic model for the study and simulation of the pantograph-rigid catenary interaction with an overlapping span," *APPLIED SCIENCES-BASEL*, vol. 11, no. 16, 2021. DOI: 10.3390/app11167445.

[8] J. Guan, J. Wu, J. Zhang, and Z. Liang, "The establishment and validation of pantograph and overhead conductor rail dynamic simulation," *Energy Reports*, vol. 8, no. 13, pp. 1247–1256, 2022. DOI: 10.1016/j.egyr.2022.08.059.

[9] M. Bruner, "Pantograph-rigid overhead interaction: A simplified method of analysis; interazione pantografo-catenaria rigida: Un metodo di analisi semplificato," *Ingegneria Ferroviaria*, vol. 78, no. 4, pp. 293–330, 2023.

[10] X. Feng, S. Gao, Y. Song, Z. Hu, L. Chen, and T. Liang, "Static and dynamic analysis of conductor rail with large cross-sectional moment of inertia in rigid catenary systems," *Energies*, vol. 16, no. 4, 2023. DOI: 10.3390/en16041810.

[11] C. Li, Y. Wang, J. Guo, and H. Peng, "Analysis of pantograph-rigid catenary coupling characteristics considering ambient temperature in western plateau," in *2025 International Conference on Electrical Engineering, Automation and Information Science (EEAIS)*, 2025, pp. 221–224. DOI: 10.1109/EEAIS66172.2025.11171185.

[12] A. Bautista, J. Montesinos, and P. Pintado, "Dynamic interaction between pantograph and rigid overhead lines using a coupled fem - multibody procedure," *Mechanism and Machine Theory*, vol. 97, pp. 100–111, 2016. DOI: 10.1016/j.mechmachtheory.2015.10.009.

[13] M. J. Page *et al.*, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ (Clinical research ed.)*, vol. 372, n71, 2021. DOI: 10.1136/bmj.n71.

[14] J. de Dios Sanz, A. Calvo, and D. Barbado, "Analysis of the capability of non-specific simulation software for studying the dynamic interaction between pantograph and rigid overhead conductor rail," in *XIII CONFERENCE ON TRANSPORT ENGINEERING, CIT2018*, P. Luque and Da Mantaras, Eds., ser. Transportation Research Procedia, vol. 33, SARA BURGERHARTSTRAAT 25, PO BOX 211, 1000 AE AMSTERDAM, NETHERLANDS: ELSEVIER SCIENCE BV, 2018, pp. 187–194. DOI: 10.1016/j.trpro.2018.10.091.

[15] L. Chen, Z. Liu, J. Zhang, and Z. Hu, "Influence of key parameters on high speed overhead conductor rail and pantograph system," *Lecture Notes in Mechanical Engineering*, pp. 201–211, 2020. DOI: 10.1007/978-3-030-38077-9_25.

[16] L. Chen, F. Duan, Y. Song, Z. Hu, Z. Liu, and X. Feng, "Assessment of dynamic interaction performance of high-speed pantograph and overhead conductor rail system," *IEEE Transactions on Instrumentation and Measurement*, vol. 71, 2022. DOI: 10.1109/TIM.2021.3135340.

[17] L. Chen, Y. Song, F. Duan, Z. Hu, W. Chu, and Z. Liu, "Wave propagation analysis of the overhead conductor rail system based on numerical simulation and full-scale experiment," *Mechanism and Machine Theory*, vol. 202, 2024. DOI: 10.1016/j.mechmachtheory.2024.105769.

[18] Y. Wang, Q. Huang, X. Chen, G. Zhao, and X. Mu, "Dynamic characteristics analysis of double pantograph catenary of ac rigid catenary system," *IEEE Access*, vol. 11, pp. 70 396–70 407, 2023. DOI: 10.1109/ACCESS.2023.3293151.

[19] J. Guo, Y. Wang, C. Li, and Y. Wang, "Dynamic performance analysis of different spans in rigid catenary," *Journal of Physics: Conference Series*, vol. 3030, no. 1, 2025. DOI: 10.1088/1742-6596/3030/1/012016.

[20] W. Qi, W. Qiao, J. Wang, and G. Mei, "Research on active control of pantograph and overhead conductor rail system based on nonlinear dynamic model," *JOURNAL OF VIBRATION AND CONTROL*, 2025. DOI: 10.1177/10775463251374730.

[21] Z. Hu, L. Chen, Y. Song, Z. Liu, and P. Antunes, "A deep learning-based surrogate model for dynamic interaction assessment of high-speed overhead conductor rail system," *Engineering Structures*, vol. 343, no. C, 2025. DOI: 10.1016/j.engstruct.2025.121221.

[22] Q. Wu, X. P. Gu, Z. Ma, and A. Wang, "A study on the vibration characteristics and damage mechanism of pantograph strips in a railway electrification system," *Machines*, vol. 10, no. 8, 2022. DOI: 10.3390/machines10080710.

[23] X. Zhi *et al.*, "A coupled approach and analysis to pantograph-rigid catenary system considering the contact pair wear and system dynamic interaction," *Mechanical Systems and Signal Processing*, vol. 239, 2025. DOI: 10.1016/j.ymssp.2025.113281.

[24] M. Simarro, S. Postigo, M. Prado-Novoa, A. Perez-Blanca, and J. J. Castillo, "Analysis of contact forces between the pantograph and the overhead conductor rail using a validated finite element model," *Engineering Structures*, vol. 225, 2020. DOI: 10.1016/j.engstruct.2020.111265.

[25] M. Simarro, S. Postigo, C. Casanueva, L. Rodriguez-Tembleque, and J. J. Castillo, "Influence of main operating conditions on contact wire wear of rigid catenary lines," *Tribology International*, vol. 196, 2024. DOI: 10.1016/j.triboint.2024.109708.

[26] M. Simarro, S. Postigo, P. Reyes, R. J. Luque, P. V. Bacic, and J. J. Castillo, "A study on the dynamic response of the double pantograph interaction with rigid catenary," *Engineering Structures*, vol. 334, 2025. DOI: 10.1016/j.engstruct.2025.120234.

[27] Z. Hu, Z. Liu, F. Duan, and L. Chen, "Assessment of contact quality in rigid catenary considering the structural parameters," *Lecture Notes in Electrical Engineering*, vol. 864 LNEE, pp. 654–665, 2022. DOI: 10.1007/978-981-16-9905-4_74.

[28] K. Chen, Y. Song, X. Lu, and F. Duan, "Sensitivity analysis and optimisation of key parameters for railway rigid overhead system and pantograph," *Sustainability (Switzerland)*, vol. 15, no. 8, 2023. DOI: 10.3390/su15086803.

[29] X. Feng, Z. Hu, S. Gao, F. Duan, W. Chu, and Y. Song, "Modelling and analysis of expansion joints' effect on dynamic performance of railway rigid overhead system," *Sensors*, vol. 23, no. 15, 2023. DOI: 10.3390/s23156797.

[30] A. Li, Y. Song, L. Chen, Z. Hu, K. Li, and Z. Liu, "Contact wire height irregularity stochastics and effect on pantograph–overhead conductor rail system," *IEEE Transactions on Instrumentation and Measurement*, vol. 75, pp. 1–11, 2026. DOI: 10.1109/TIM.2025.3645931.

[31] Z. Hu, Y. Song, L. Chen, F. Duan, Z. Liu, and X. Feng, "Experimental and numerical exploration of support stiffness influence on the current collection quality of pantograph and overhead conductor rail system," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 3, pp. 7112–7126, 2024. DOI: 10.1109/TTE.2023.3345955.

[32] Z. Mo, M. Zeng, and J. Guan, "Analysis of the dynamic performance between pantograph and rigid conductor rail considering construction error of the contact wire height," *Lecture Notes in Electrical Engineering*, vol. 864 LNEE, pp. 502–514, 2022. DOI: 10.1007/978-981-16-9905-4_58.

[33] F. Duan, Y. Song, Z. Liu, and H. Ma, "Dynamic performance of railway rigid–flexible catenary transition section based on experimental and numerical approaches," *IEEE Transactions on Instrumentation and Measurement*, vol. 74, 2025. DOI: 10.1109/TIM.2025.3636633.

[34] Á. Calvo-Hernández, Sanz Bobi, Juan de Dios, J. G. Fernández, and A. Badolato Martin, "Vibration reduction on overhead contact rails: A simulation-optimization approach," *International Journal of Simulation Modelling*, vol. 20, no. 2, pp. 315–326, 2021. DOI: 10.2507/IJSIMM20-2-561.

[35] W. Qi, H. Yu, C. Peng, G. Mei, J. Zhang, and W. Zhang, "Impact of metro pantograph raising height, stagger, and longitudinal load on component strain: Experimental validation and optimization," *Engineering Failure Analysis*, vol. 186, 2026. DOI: 10.1016/j.engfailanal.2025.110494.

[36] X. Zhao, S. Wang, X. Chen, Y. Wang, and Z. Chang, "The fluid-structure interaction characteristics of the pantograph-rigid catenary in the context of extra-long tunnels," *ELECTRONICS*, vol. 14, no. 8, 2025. DOI: 10.3390/electronics14081628.

[37] S. Strano, M. Terzo, and C. Tordela, Eds., *Multipurpose model for pantograph dynamic interaction with flexible or rigid catenary*, 2021. DOI: 10.1109/RTSI50628.2021.9597261.

[38] G. Mei, X. Li, and W. Zhang, "Study on the friction-induced vibration and wire corrugation of metro rigid overhead wire-pantograph systems," *JOURNAL OF VIBRATION AND CONTROL*, vol. 30, no. 19-20, pp. 4450–4464, 2024. DOI: 10.1177/10775463231210336.

[39] K. Yamashita, K. Kitajo, S. Wada, T. Sugiura, and H. Yabuno, "Impact oscillations with multiple modes between a pantograph and an overhead rigid conductor line in a railway current collection system," *JVC/Journal of Vibration and Control*, vol. 18, no. 4, pp. 499–508, 2012. DOI: 10.1177/1077546310380430.

[40] N. Nishiyama and K. Yamashita, "Suppression of impact oscillations in a railway current collection system with an additional oscillatory system," *Springer Proceedings in Mathematics and Statistics*, vol. 364, pp. 15–22, 2021. DOI: 10.1007/978-3-030-77314-4_2.

[41] T. Koyama and M. Aboshi, "Formation mechanism of undulating wear on overhead conductor rails due to dynamic characteristics of pantographs," *Quarterly Report of RTRI (Railway Technical Research Institute)*, vol. 54, no. 1, pp. 18–23, 2013. DOI: 10.2219/rtriqr.54.18.

[42] J. Ai, J. Ruan, H. Li, J. Zhang, and W. Gao, "A lumped-mass model of overhead conductor rail considering the height of contact wire for active pantograph," in *2024 4th International Conference on Electrical Engineering and Control Science (IC2ECS)*, 2024, pp. 392–397. DOI: 10.1109/IC2ECS64405.2024.10928690.

[43] W. Xu, T. Wu, J. Wu, D. Qin, and Y. Li, "Research and optimisation of the coupling performance of pantograph–catenary system based on numerical simulation and experimental tests," *Lecture Notes in Electrical Engineering*, vol. 1084 LNEE, pp. 329–341, 2023. DOI: 10.1007/978-981-99-6431-4_28.

[44] W. Qi, J. Wang, G. Mei, and W. Zhang, "Active control strategy of pantograph coupling with rigid catenary considering the time delay in sensor and actuator," *Lecture Notes in Mechanical Engineering*, pp. 144–157, 2022. DOI: 10.1007/978-3-031-07305-2_16.

[45] M. Tan, H. Li, and L. Nie, "Defect diagnosis of rigid catenary system based on pantograph vibration performance," *Actuators*, vol. 13, no. 5, 2024. DOI: 10.3390/act13050162.

[46] J. Qiu *et al.*, "Analysis of the current collection quality of the variable speed zone of the pantograph-catenary system," *Lecture Notes in Mechanical Engineering*, pp. 196–200, 2020. DOI: 10.1007/978-3-030-38077-9_24.