Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 9.1
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.9.1

Experimental and Numerical Study of the Thermal Behaviour in Tread Braked Wheels: Recent Developments

N. Bosso, M. Magelli, R. Pagano and N. Zampieri

**Department of Mechanical and Aerospace Engineering,
Politecnico di Torino, Italy**

Abstract

Tread braking remains the most widely adopted solution for freight trains due to its robustness and low cost, despite its complex thermo-mechanical behaviour. The frictional contact between brake blocks and wheel treads generates cyclic thermal loads that may lead to material degradation, thermal fatigue, and crack initiation. This paper presents recent developments by the Politecnico di Torino in the investigation of wheel-shoe interaction, achieved through both experimental and numerical approaches. As a key contribution, the research team has designed and built an innovative scaled twin-disc test rig, that relies on a dedicated thermal similitude rule, ensuring that the temperature field on the scaled device corresponds to the one that would be obtained on the full-scale system. The experimental setup can be integrated with different sensors, i.e., thermal image camera and a battery of pyrometers, to obtain the temperature field with high resolution and sampling rate. In parallel, the research group has been working on the development of numerical thermal models for the brake block and wheel with different levels of modelling complexity. The developed experimental and numerical tools support model validation, parametric analyses, and experimental testing, to gain further insights into the wheel-shoe contact interaction.

Keywords: tread braking, wheel-shoe contact, twin-disc, finite element analysis, thermal similitude, experimental validation.

1 Introduction

Tread braking is still the most employed braking system installed on freight trains, thanks to its robustness, simplicity, and low manufacturing cost [1]. In spite of its simple working principle, based on pressing friction materials against the wheel tread surface, simplicity, tread braking exhibits complex thermo-mechanical behaviour. With tread braking, kinetic energy is dissipated in the form of heat, with the generation of a friction heat flux that raises the temperature in both the wheel and braked shoes. Due to wheel rotation, each point on the wheel surface undergoes a cyclic thermal loading, alternating between heating when in contact with the block and cooling when exposed to ambient air. This cyclic load may be responsible for local metallurgical transformations, thermal fatigue, and crack initiation/propagation [2].

Gaining a deep understanding of the thermo-mechanical behaviour of tread braked wheels and blocks is the key to promptly detect wheel damage phenomena, as well as to improve maintenance scheduling and planning of brake blocks replacements. Nowadays, a big research effort is needed, as traditional phosphorous cast iron (P10) shoes have been replaced with composite materials, that whilst complying with the requirements of the TSI Noise regulation [3], exhibit low thermal conductivity, with higher thermal aggressiveness on the wheel.

Numerical models [4,5], commonly relying on the finite element (FE) method, allow to investigate the interaction between the wheel and shoes, however, due to the complex phenomena involved, experimental data is essential to improve their robustness and reliability. On-track [6] and full-scale [7,8] tests reproduce realistic operating conditions, but they are costly, time-consuming, and often difficult to control. On the other hand, small-scale laboratory devices [9,10] simplify control of the test conditions, improving repeatability whilst reducing costs and the time required for experimental campaigns. However, small-scale laboratory devices such as common pin-on-disc and twin-disc machines do not comply with scaling rules [11], hence making it difficult to extend test results to real-world operating scenarios, so that they are most suited for qualitative and comparative studies.

The Politecnico di Torino (PoliTo) railway research group has been conducting a comprehensive research activity on the wheel-shoe interaction, combining experimental testing and numerical simulations. As a major contribution, the activity includes the design of an innovative scaled twin-disc test rig, that follows a specifically conceived thermal scaling rule, which makes it possible to correlate the temperature field observed on the bench with real-world conditions. At the same time, the PoliTo research team has developed numerical thermal models for the calculation of the temperature field of tread braked wheels and blocks, with different levels of complexity, which makes them suited for several possible final applications.

This paper intends to provide an overview of the recent developments achieved at PoliTo, framed within the broader state of the art in the field of wheel-shoe interaction. Emphasis is placed on the integration of experimental and numerical methodologies.

2 Experimental Framework: The Scaled Twin-Disc Rig

The experimental activity focuses on a scaled twin-disc test rig, specifically designed to reproduce wheel–rail contact conditions and subsequently upgraded to investigate tread braking phenomena. The original rig configuration [12] was conceived for wear analysis at the wheel–rail interface. It consists of two discs representing the wheel (upper one) and the rail (lower one), mounted on independent shafts and driven by electric motors. The normal force pressing the rollers is controlled by an elastic loading system, as shown in Figure 1.

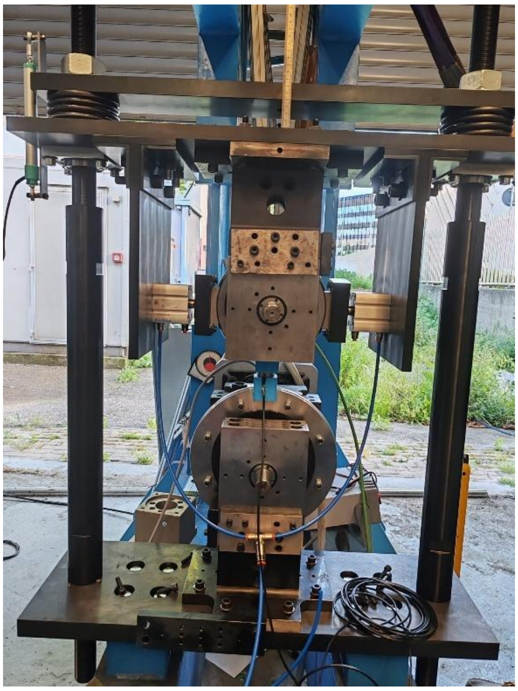

Figure 1: Twin disk test bench designed by PoliTo railway research team.

The geometry of the test facility is scaled 1:5 according to Pascal's similitude, which allows to reproduce the full-scale contact pressures despite the reduced dimensions of the system. A key advancement in the research program is the extension of the rig to include a scaled tread braking system. This upgrade allows the simulation of frictional contact between brake blocks and the wheel tread, enabling the investigation of thermal phenomena directly related to braking. The design of the braking system required careful consideration of scaling laws, to have a unitary scaling factor of the temperature. Precisely, a dedicated thermal similitude model was developed to ensure that the temperature field observed in the scaled system is representative of the full-scale case during drag braking operations [13]. This was achieved by deriving appropriate scaling factors for relevant quantities such as heat flux, time, and convection coefficients. The proposed thermal scaling technique is currently limited to drag braking scenarios, due to the physical constraints of the motors available on the test bench. According to this scaling approach, the time scaling factor is proportional to the square of the geometric scaling factor. Consequently, when attempting to reproduce stop braking maneuvers, the required deceleration becomes unrealistically high for the capabilities of the experimental setup.

The braking system consists of pneumatic actuators controlled by proportional valves that allows to precisely control the cylinder pressure and hence the braking force. Both single-block (1Bg) and double-block (2Bg) configurations can be reproduced, allowing flexibility in experimental conditions. The modular design of the system ensures ease of replacement and adaptation of brake blocks made from different materials. The position of the brake block holder can be easily regulated before running the test in order to modify the relative position between the wheel tread and the brake block. The test rig is equipped with a comprehensive instrumentation system. Sensors are used to measure rotational speeds of both rollers, braking torques, and applied forces by the pneumatic cylinders, enabling the calculation of the dissipated mechanical power during braking. This information is used to estimate the total heat flux generated at the contact interface. The bench can be equipped with an infrared thermal camera to measure the temperature field on the lateral surfaces of the wheel and brake blocks. This technique provides high resolution without interfering with the system dynamics. The use of high-emissivity coatings ensures accurate temperature measurements across the observed surfaces. In order to measure the temperature on the wheel tread, the test bench can also be equipped with several pyrometers, which allow for localized temperature measurements on small spots of the wheel surface. The use of pyrometers is not limited to the wheel tread, as dedicated supporting plates enable their installation on the sides of the test bench to measure the temperature of both the wheel and the brake shoe lateral surfaces, see Figure 2.

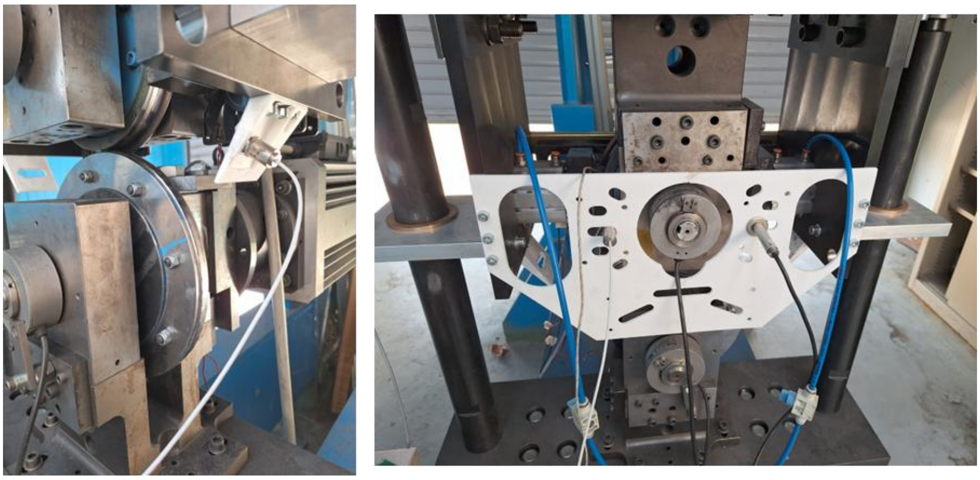

Figure 2: Measuring system based on pyrometers installed on the test bench.

The availability of such a controlled experimental platform represents a fundamental asset for the validation of numerical models. It enables repeatable tests under well-defined conditions, which are essential for systematic model calibration and comparison. The test bench will be also exploited to define an experimental setup to experimentally measure the partition coefficient between the wheel and the brake shoe.

3 Thermal Modelling of Brake Blocks

The PoliTo railway research group has developed numerical models of the brake block with increasing levels of complexity, to make them suited for different possible applications. To include the calculation of the brake block temperature field evolution during braking within a multibody (MB), framework, a mono-dimensional (1D) model is available [14]. The 1D brake block model relies on the finite differences method (FDM) for the solution, and it calculates the temperature distribution along the radial direction, hence neglecting the thermal conduction along the axial and circumferential direction, see Figure 3a). This modelling assumption is based on the results of 3D literature models [15], showing that the temperature of the brake block is approximately constants in radial layers, with minor gradients along axial and circumferential directions. In view of its simplicity, the 1D FDM brake block model is integrated within the MB formalism of the SIMPACK commercial MB code, through the definition of user-force elements with dynamic states, corresponding to the temperature evolution at different radial locations on the block. This approach leads the path towards building models coupling the mechanical and thermal fields, e.g., with the definition of wheel-shoe friction coefficient depending on temperature, with no need for complex co-simulation techniques. This was done in collaboration with research from the Centre for Railway Engineering (CRE) at Central Queensland University (CQU) as shown in [16], where a 1D model, based on the heat balance of radial shoe layers, is integrated within a longitudinal train dynamics (LTD) simulation code. Simulations show that the temperature dependency of the brake-shoe friction coefficient can increase train braking distances. Overall, the main advantage of 1D models is the excellent computational efficiency, but simplified modelling may raise some concerns about numerical accuracy.

To improve modeling accuracy, the PoliTo railway research group has built 2D plane models of brake blocks, implemented as ANSYS APDL routines. A simplified model, approximating the shoe as a circular sector, and configured to consider scaling effect, was used to validate the thermal similitude rule specifically conceived to design the tread braking system installed on the scaled twin-disc test rig [13], see Figure 3b). A similar model for the scaled brake shoe mounted on the scaled twin-disc rig was used for the purpose of model tuning according to experimental data. The model meshes the shoe geometry with plane thermal elements, while the brake block holder is modelled as a lumped thermal mass, connected to the shoe outer surface with conduction link elements. Based on experimental observations, the model enables the definition of a heat flux BC on the shoe inner surface, that follows a Gaussian distribution along the circumferential direction. On the other hand, on the lateral sides of the shoe, a convective BC is specified. As shown in [17], main parameters of the 2D plane model that are tuned based on experimental data include the angular width of the Gaussian function describing the heat flux distribution (related to the standard deviation), the convection coefficient, the heat partitioning factor and the radial coordinate of the lumped thermal capacitance representing the brake block holder. Preliminary results show that an acceptable agreement can be achieved with the 2D plane model thanks to its good compromise between modelling accuracy and computational speed, especially during the braking. Some deviations are observed during the cooling phase, mainly because the model misses the correct simulation of the convection heat flux along the axial direction. Therefore, future work is going to focus on improving the modelling accuracy and on performing additional experimental tests, to increase the size and robustness of the dataset used for model tuning and validation.

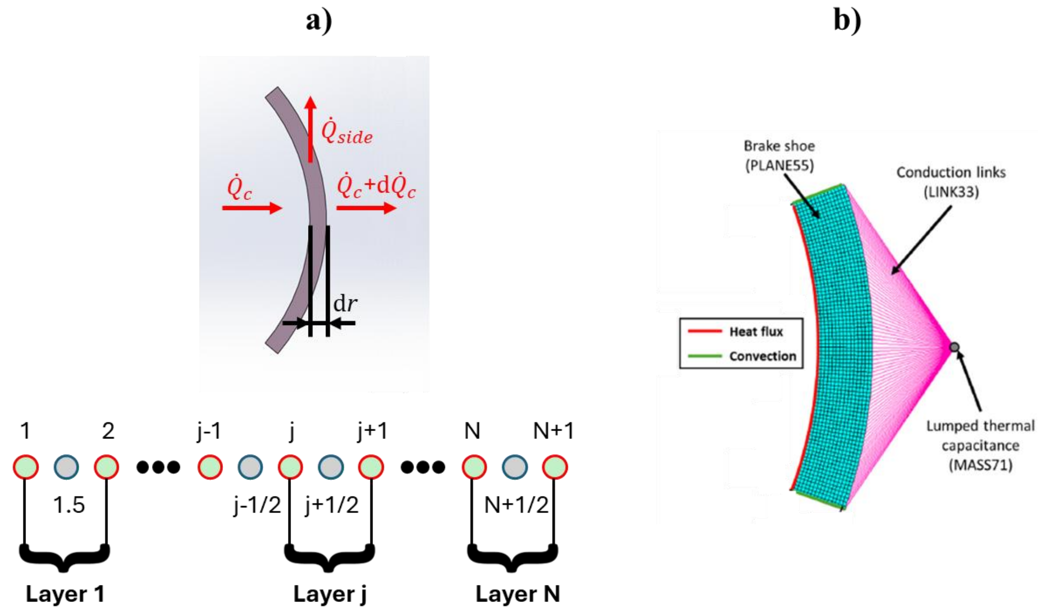

Figure 3: Brake block numerical thermal models: a) 1D FMD model (heat balance for a single layer and computational grid) and b) 2D plane FE model.

4 Thermal Modelling of Railway Wheels

The thermal analysis of railway wheels requires accounting for the coupling between mechanical contact and heat generation, but usually the two problems are solved independently, neglecting the thermo-mechanical coupling. The FE models of the wheel, developed by the PoliTo research group, can be divided into three types: 2D planar models, 2D axisymmetric models and 3D models. The 2D planar thermal model [18], which is the first one developed by the research group, first calculates the contact pressure distribution using a structural analysis. This distribution is then used to obtain the heat flux applied to the wheel surface. This approach provides a detailed representation of thermal gradients within the radial and circumferential direction and allows investigating the influence of contact mechanics on temperature evolution but neglects the variation of the temperature along the axial direction. An example of this type of model is shown in Figure 4a).

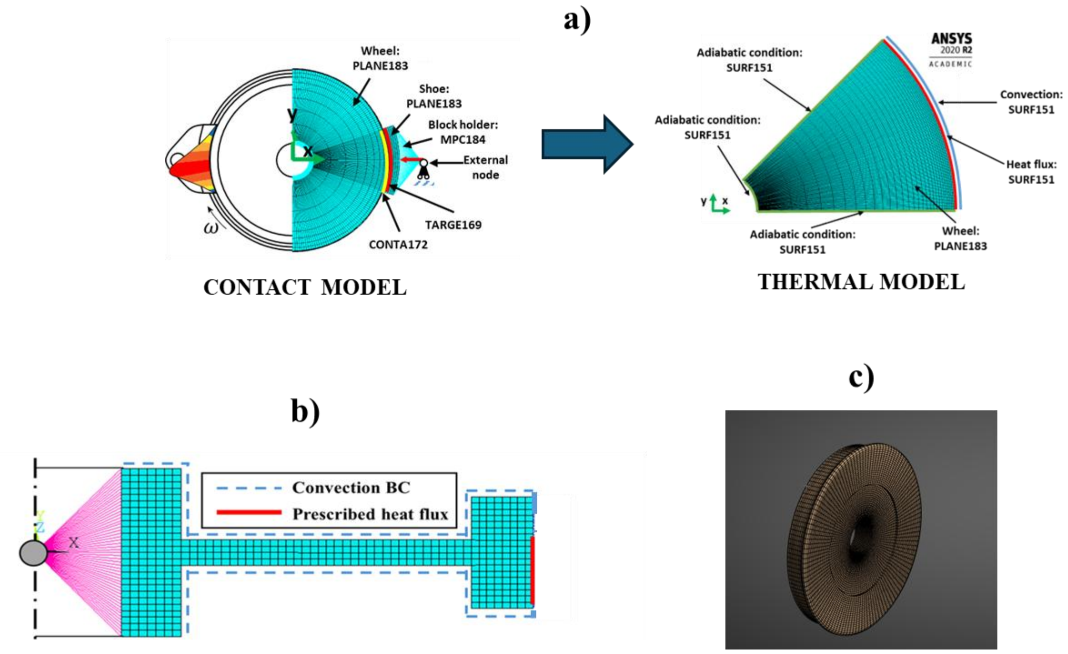

Figure 4: Different FE approaches to realize the wheel FE model: a) 2D planar, b) axisymmetric, c) 3D.

Axisymmetric models are widely used due to their computational efficiency [19]. Figure 4b) depicts a simplified cross section model of a tread braked wheel with element mesh and boundary conditions (BCs). By assuming rotational symmetry, the problem is reduced to a two-dimensional domain defined by the wheel cross-section. However, this approach relies on the assumption of uniform thermal loads along the circumferential direction. In tread braking systems, this assumption is not strictly valid, as the heat input is localized in the regions of contact with the brake blocks. Therefore, classical axisymmetric models are unable to predict temperature variations along the wheel circumference and tend to provide only average temperature values. Nevertheless, experimental evidence and numerical studies have shown that in certain operating conditions, particularly during steady-state operations, the circumferential variation of temperature may be approximated by its mean value. This observation justifies the use of axisymmetric models for preliminary analyses [20,21].

To overcome the limitations of classical axisymmetric models, an advanced modelling approach has been introduced, based on harmonic axisymmetric finite elements [22]. In this formulation, the non-uniform heat flux is expressed as a Fourier series along the circumferential coordinate. Each harmonic component represents a spatial variation of the thermal load and is treated as an independent problem. The overall temperature field is obtained by superimposing the contributions of all harmonic components. This approach combines the advantages of axisymmetric geometry with the ability to capture circumferential variations of the temperature field. Additionally, due to the orthogonality properties of Fourier functions, the different harmonic components can be solved independently, allowing efficient parallelization and reduced computational effort.

Benchmark comparisons have demonstrated that the harmonic axisymmetric model can reproduce the results of full 3D simulations, see Figure 4c), with high accuracy, while requiring significantly lower computational resources.

5 Conclusions

This paper has presented recent developments in the study of thermal behaviour in tread-braked railway wheels, focusing on the research activity carried out by the PoliTo railway research group combining experimental and numerical methodologies. The main contributions include the development of an innovative scaled test rig, the formulation of thermal models with different levels of modelling complexity, and the experimental validation of these models using thermal imaging techniques. The results confirm that the proposed framework provides an effective balance between accuracy and computational efficiency, enabling detailed analysis as well as system-level simulations.

Furthermore, the developed modelling framework represents a solid foundation for the implementation of digital twins of tread braking systems, enabling real-time prediction and monitoring of the wheel thermal behavior. In this context, these models are currently being employed within the FISA project AI4FREIGHT, where they will be used to developed real-time algorithms used to monitor the wheel temperature.

Future work will focus on extending the validation to wheel models, improving the representation of heat partitioning, and integrating thermal and mechanical effects within comprehensive simulation environments.

Acknowledgements

Nicolò Zampieri received financial support by Government of Italy Ministry of University and Research (MUR), grant number FISA-2023-00314.

References

[1] G. Megna, A. Bracciali, "Tread-Braked Wheels: Review and Recent Findings", Machines, 13(7), 2025.
[2] E.V. Landström, T. Vernersson, R. Lundén, "Analysis and testing of tread braked railway wheel — Effects of hot spots on wheel performance", International Journal of Fatigue, 180, 2024.
[3] Commission Regulation (EU) of 23 December 2005 Concerning the Technical Specification for Interoperability Relating to the Subsystem ‘Rolling Stock Noise’ of the Trans-European Conventional Rail System. 2006
[4] P. Wasilewski, "Frictional Heating in Railway Brakes: A Review of Numerical Models", Archives of Computational Methods in Engineering, 27(1), 45-58,2020.

[5] L. Tran, J. Cookson, W.K Chiu, R. Saporito, "A review of thermal railway wheel modelling – Applicability and limitations", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 240(5), 539-554, 2026.
[6] M.S. Walia, T. Vernersson, R. Lundén, et al., "Temperatures and wear at railway tread braking: Field experiments and simulations", Wear, 440-441, 2019.
[7] T. Vernersson, "Temperatures at railway tread braking. Part 2: calibration and numerical examples", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 221(4), 429-441, 2007.
[8] K. Ikeuchi, K. Handa, R. Lundén, T. Vernersson, "Wheel tread profile evolution for combined block braking and wheel–rail contact: Results from dynamometer experiments", Wear, 366-367, 310-315, 2016.
[9] L.Ghidini, T. Vernersson, M. Faccoli, A. Mazzù, "Optimization and validation of a thermal simulation model for tread braking using an innovative small-scale experimental rig", International Journal of Rail Transportation, 14(1), 72-89, 2026.
[10] L.Ghidini, F. Zanardi, A. Mazzù, M. Faccoli, "Innovative small-scale testing to investigate thermo-mechanical damage in tread-braked railway wheel steel paired with various types of cast iron", Wear, 574-575, 2025.
[11] N. Bosso, P. Allen, N. Zampieri, "Scale Testing Theory and Approaches", in "Handbook of Railway Vehicle Dynamics", S. Iwnicki, M. Spiryagin, C. Cole, T. McSweeney (Editors), CRC Press: Boca Raton, FL, USA, Chapter 20, 825-867, 2019.
[12] M. Magelli, R. Pagano, N. Zampieri, "Design of an Innovative Twin-Disc Device for the Evaluation of Wheel and Rail Profile Wear", Designs, 8(4), 2024.
[13] M. Magelli, R. Pagano, N. Zampieri, "Adapting a scaled twin-disc device for tread braking investigations based on an ad-hoc thermal similitude model", Wear, 574-575, 2025.
[14] M. Magelli, N. Zampieri, Q. Wu, "Integration of brake block thermal equations within a railway vehicle multibody model: a multiphysics approach", International Journal of Rail Transportation, 2024.
[15] A. Somà, M. Aimar, N. Zampieri, "Simulation of the Thermal Behavior of Cast Iron Brake Block during Braking Maneuvers", Applied Sciences, 11(11), 2021.
[16] Q. Wu, M Magelli, N. Zampieri, E. Bernal, "Adding a brake shoe temperature model into freight train longitudinal braking dynamics simulations", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*,* 237(5), 631-641, 2023.
[17] M. Beltramo, N. Bosso, M. Magelli, R. Pagano, M. Scapin, N. Zampieri, "Experimental validation of a numerical thermal model for railway brake blocks with experimental data obtained on a twin-disc rig", Presented at: “13th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2025)”, Tokyo, Japan 22-26 September 2025.

[18] N. Bosso, L. Cantone, G. Falcitelli, et al., "Simulation of the thermo-mechanical behaviour of tread braked railway wheels by means of a 2D finite element model", Tribology International, 178, 2023.
[19] T. Vernersson, "Temperatures at railway tread braking. Part 1: Modelling", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 221(2), 167-182, 2007.
[20] A. Yevtushenko, M. Kuciej, P. Grzes, P. Wasilewski, "Methodology of estimation of temperature mode in the 2xBgu type railway braking system", Scientific reports, 12(1), 2022.
[21] M. Kuciej, P. Grzes, P. Wasilewski, "A Comparison of 3D and 2D FE Frictional Heating Models for Long and Variable Applications of Railway Tread Brake", Materials, 13(21),2020.
[22] M. Magelli, N. Zampieri, "A new finite element axisymmetric model with non-axisymmetric thermal loads for thermal analyses of tread braked wheels", Tribology International, 209, 2025.