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Dynamic Response of Dual-Gauge Railway Turnouts Under Mixed Traffic: Experimental Validation and Hybrid FEM–DEM Modelling

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Abstract

Railway turnouts represent one of the most critical components of railway infrastructure due to the presence of geometric and mechanical discontinuities, which generate high dynamic loads at the wheel–rail interface. This issue is particularly pronounced in dual-gauge tracks, and especially in dual-gauge turnouts. Dual-gauge turnouts extend the concept of dual-gauge track to the realm of track switching. These devices must cater to the operational requirements of both gauges, ensuring that trains of differing specifications can safely merge, diverge, or cross paths without compromising performance. The complexity stems from the need to maintain proper alignment, flangeway gaps, and clearances for both track types. Thus, this research focuses on analysing the dynamic behaviour of dual-gauge turnouts, with particular focus on ballast and sub-ballast degradation induced by dynamic loads generated by passing rolling stock. A methodology based on hybrid numerical models is employed, combining the Finite Element Method (FEM), applied to track superstructure elements (rails, sleepers, and fastening systems), with the Discrete Element Method (DEM), used for detailed simulation of ballast and the sleeper–ballast contact interface. The analysis is supported by experimental data obtained from in-situ measurements on the through route of the turnout, allowing the evaluation of key aspects such as ballast particle displacement, force distribution, and stress propagation under different dynamic load scenarios associated with the turnout's geometry and stiffness. The findings of this study provide technical guidelines for the optimisation of dual-gauge turnout design and maintenance, contributing to improved structural

integrity of the railway infrastructure, reduced maintenance costs, and extended track service life.

Keywords: dual gauge turnout, FEM model, ballast degradation, discrete element method (DEM), track stiffness, dynamic behaviour.

1 Introduction

Dual-gauge turnouts are a key enabling technology for interoperability in Spain, where the historical Iberian gauge (1,668 mm) network coexists with an expanding standard-gauge (1,435 mm) high-speed system. As Spain has progressively extended standard-gauge corridors to connect with the wider European network, the interface between both gauges has become a strategic operational issue: passenger and freight services must be routed across networks with different track gauges without compromising capacity, safety, or maintenance performance.

However, designing dual-gauge turnouts is inherently complex, since they comprise a double crossing, an obtuse crossing, and five switch–stock rail interfaces, including the two associated with the obtuse crossing. Engineers have to juggle many variables at once. A central technical issue is the flangeway gap, the clearance beside the rail that allows the wheel flange to pass. If that gap varies along the crossing or check-rail zones, it can provoke poor guidance, irregular wheel–rail contact, and in the worst case, derailment risk. In practice, a workable solution typically requires a consistent flangeway dimension shared by both gauges, which makes this parameter a critical constraint and not something that can be treated as optional.

Turnout geometry must also be compatible with different wheel profiles. That means carefully defining alignments, angles, and radii so that trains in either gauge can move from the through route to the diverging route without abrupt steering forces or unstable dynamics. To reach that balance, teams rely on advanced simulation to anticipate vehicle–track interaction and refine the design.

Maintenance adds a further dimension. With more components and interfaces than a conventional turnout, dual-gauge turnouts require more frequent inspection and tighter maintenance schedules, especially in high-load zones such as crossings and check rails. Because two systems share the same assets, small degradations can propagate faster into performance or safety issues.

Within this context, dual-gauge turnouts are used to manage transitions and operational flexibility in corridors where mixed traffic is required, supporting connections between Iberian-gauge conventional lines and standard-gauge high-speed or upgraded routes, allowing connectivity between the Spanish railway system and the Trans-European Transport Network. Consequently, in Spain these turnouts are not only an interoperability solution but also a high-maintenance asset whose performance can strongly influence network availability and life-cycle costs.

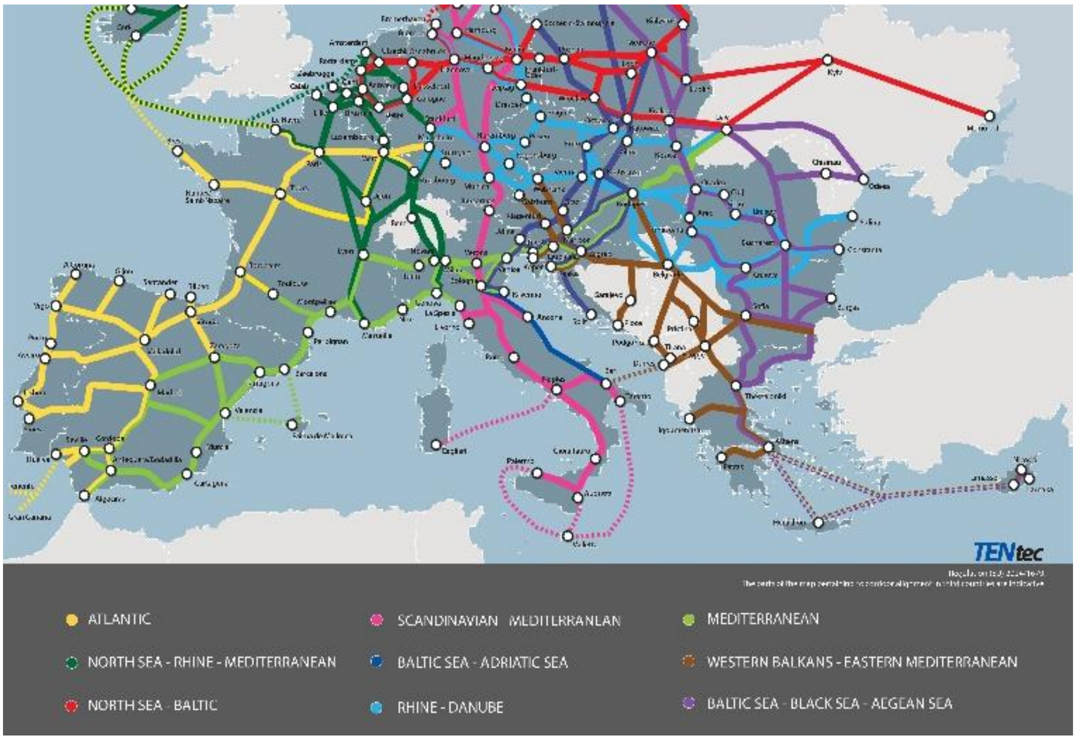

Figure 1: Trans-European Transport Network.

Despite their significance, the available scientific literature on the dynamic behaviour of railway turnouts, and particularly dual-gauge turnouts, is limited. Therefore, the present study analyses the structural behaviour of dual-gauge turnouts, taking advantage of the simplifications introduced in the numerical modelling and the availability of experimental data collected in this section during field measurement campaigns. Thus, the study builds upon the results of the project "DUAL-SWITCH: Turnout behaviour under dynamic loads and its impact on sublayers and infrastructure maintenance" (Ref. PID2020-118013RB-C22), aiming to expand previous knowledge through Discrete Element Method (DEM) modelling in YADE.

The methodology proposed employs the Finite Element Method (FEM), with particular attention to balancing model complexity and computational limitations. The system is decomposed into subelements representing rails, sleepers, and elastomeric components, ensuring accurate transmission of displacements and stresses between them.

FEM modelling is implemented in ANSYS, using customised routines to facilitate coupling with the DEM model in YADE. Model validation is performed using available field measurements from previous campaigns, ensuring that the simulations are representative of in-service behaviour and supporting a more practically applicable understanding of turnout–sublayer interaction.

2 Methods

2.1 Finite Element Method FEM

The Finite Element Method (FEM) is a widely used numerical technique for predicting the mechanical response of complex structural systems. It discretises a continuum into a mesh of finite elements connected by nodes, allowing the governing equations of motion and equilibrium to be solved with sufficient resolution to capture local effects and structural discontinuities. In railway engineering, FEM is routinely applied to analyse the behaviour of rails, sleepers, fastening systems, and turnout components under static and dynamic loading.

In recent years, several studies have employed FEM simulations to investigate the structural behaviour of railway turnouts. Specifically, [1] Mahjoubeh Sistaninia et al. (2024) modelled a swing-nose crossing with DLD using FEM, evaluating displacements, stresses, and dynamic behaviour during train passage. Their results indicated that maximum deflections and stresses (tension and compression) occur at the tip of the swing-nose crossing, although remaining below the material strength limit. [2] Mahjoubeh Sistaninia et al. (2025) analysed the dynamic behaviour of high-speed turnout components under varying speeds and axle loads, focusing on vertical displacements and contact forces. Detailed FEM analysis revealed displacement patterns in the rail, showing that at higher speeds, the crossing nose responds less efficiently to rapid load variations. [3] Shih, Jou-Yi et al. (2023) investigated the dynamic behaviour of a UIC60-760-1:15 turnout with a 760 m curve radius and 1:15 switch angle using a Multi-Body Simulation (MBS) model. The study incorporated equivalent track properties defined from the structural flexibility of the turnout and compared rail receptance and impact force results with those obtained from a FEM model. Validation results demonstrated good agreement between both models, whilst highlighting a significant reduction in computational cost in terms of calculation time and required resources.

Thus, FEM provides strong capabilities for representing complex geometries, computing detailed stress–strain fields, and handling both linear and nonlinear material and contact behaviour. However, its use for ballast modelling is inherently limited by the granular, discontinuous, and anisotropic nature of the material. When ballast is idealised as an equivalent continuum, key mechanisms such as particle rearrangement, force-chain evolution, dilation/compaction, and particle breakage cannot be represented explicitly. For this reason, the Discrete Element Method (DEM) is adopted to model ballast at the particle scale, enabling a more realistic description of its micromechanical response and the sleeper–ballast interaction under dynamic loads.

2.1.1 Software

This study focuses on configuring a FEM model to analyse the mechanical response of the superstructure of a railway turnout, with the aim of investigating the behaviour of rails, sleepers, and crossings under dynamic loads. Various approaches exist for FEM modelling, typically implemented through specialised software packages. In this research, the finite element software ANSYS is adopted, offering the possibility of custom programming via C++, which provides greater flexibility in model definition.

To manage the high geometric and mechanical complexity of a railway turnout, a simplified modelling approach is adopted. Instead of representing every component in full 3D detail, the turnout is idealised using a node–beam framework, where rails and sleepers are modelled as beam elements connected through discrete nodes. The support provided by the ballast and sublayers is represented by elastic supports and additional damping elements placed at the sleeper support locations.

This beam-spring representation significantly reduces the number of degrees of freedom and the computational cost, whilst still capturing the key mechanisms governing the turnout's global response, such as support stiffness variations, load transfer from rail to sleeper, and the overall dynamic behaviour under moving axle loads. As a result, it provides a practical and efficient way to model the turnout at full scale without sacrificing the essential structural features required for dynamic analysis.

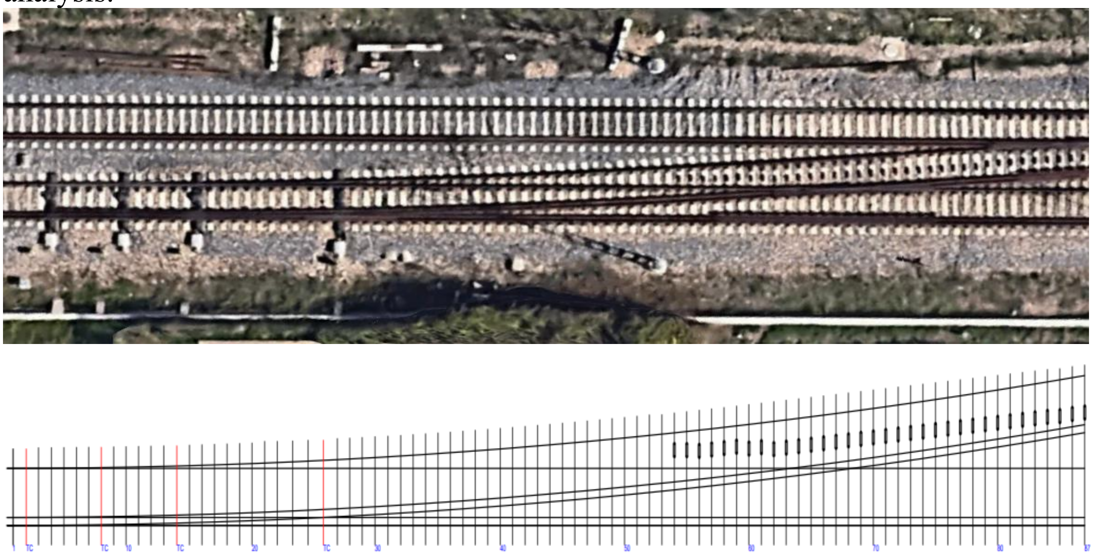

Figure 2 Dual-gauge turnouts

2.1.2 Simulation Procedure

The methodology employed in this research is based on a simplified mechanical beam–spring model, adopted due to computational limitations and the maximum number of nodes allowed by the simulation software, since it is necessary to model the entire turnout, composed of a total of 87 sleepers. In this approach, the sleeper is idealised as a beam, whilst ballast behaviour is represented by vertical springs, which provide the equivalent support stiffness.

The rail is discretely supported on the sleeper at points U1C, U2C, and U3C, representing the contact zones through which the vertical loads generated by passing axles—including associated dynamic effects—are transmitted. These loads are progressively transferred from the rail to the sleeper, which acts as a distributing element, and subsequently to the ballast, modelled through springs K1, K2, and K3, allowing the capture of non-uniform stress distribution.

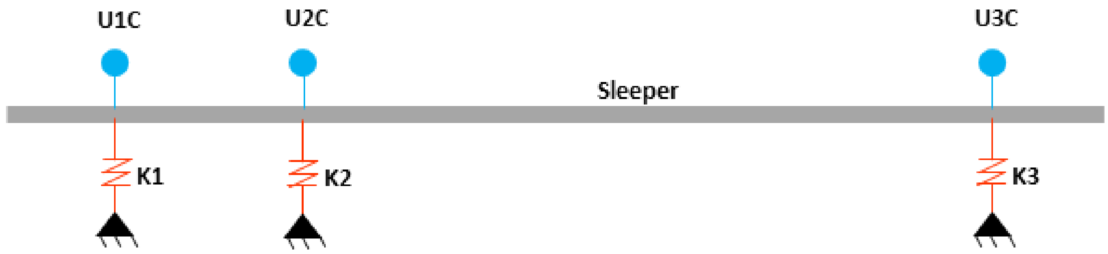

Figure 3 Simplified rail–sleeper–spring model.

The model is designed in an evolutionary manner to progressively increase its realism without significantly increasing computational cost. Initially, the ballast is represented as purely elastic springs, whilst in subsequent stages damping is introduced to model energy dissipation mechanisms associated with sleeper–ballast interaction and the dynamic effects of train passage. This extension enables a more accurate description of the rail–sleeper–ballast system's dynamic response, facilitating comparisons between models of varying complexity.

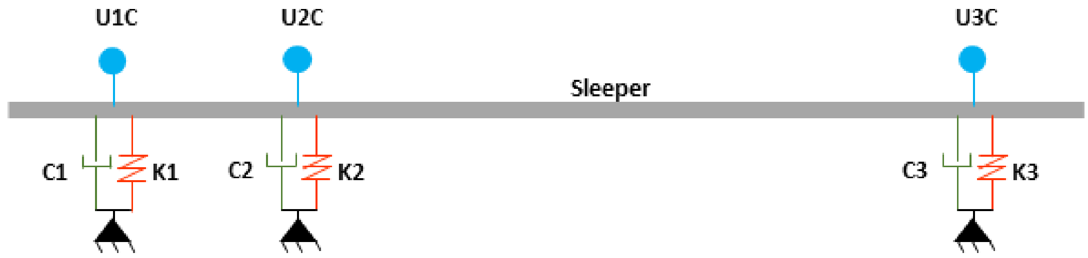

Figure 4 Simplified rail–sleeper–spring–damper model.

As a further extension of the evolutionary modelling approach, a three-dimensional simulation of a representative turnout section will be conducted in a later phase of the research to obtain a more realistic description of the structural and dynamic behaviour of the system. The 3D simulation will serve as a tool for validation and comparison of the simplified models, allowing assessment of their applicability and accuracy in representing the actual behaviour of the railway track.

2.1.3 Discrete Element Method (DEM)

DEM is particularly well-suited for the analysis of granular materials, such as railway ballast. Unlike FEM, DEM allows each ballast particle to be modelled individually, explicitly reproducing the interactions between particles.

Within the DEM framework, various modelling approaches exist, typically implemented through specialised software. In this work, the discrete element software YADE is employed, a general-purpose dynamic engine. YADE is an open-source, extensible framework primarily developed in C++, which facilitates the autonomous incorporation of new algorithms and the creation of custom interfaces. This tool enables the reproduction of granular material behaviour under varying loading and boundary conditions.

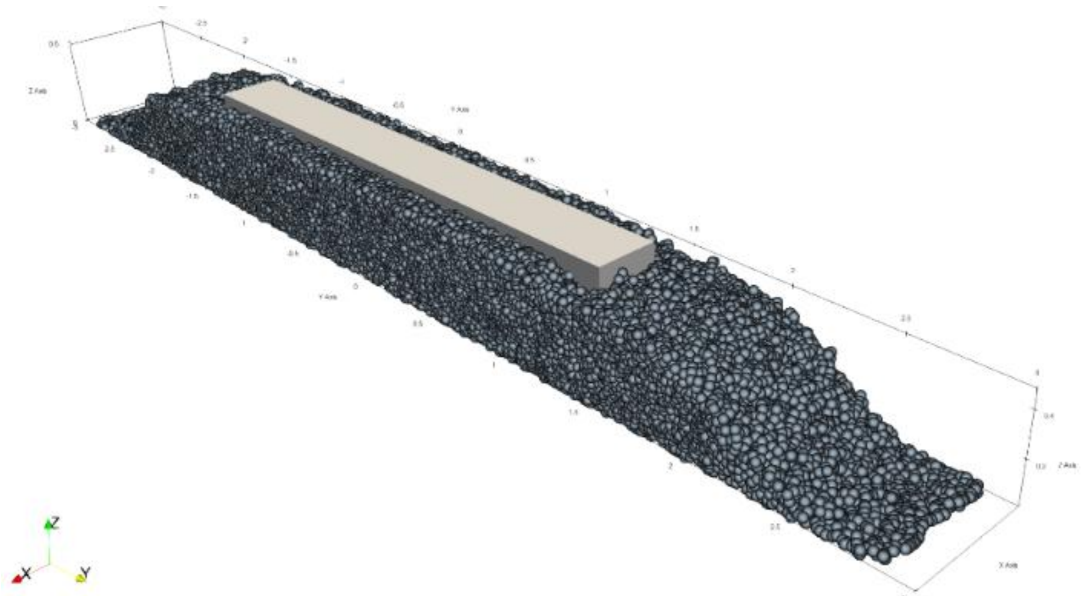

Figure 5 DEM model of the sleeper under crossing area.

2.1.4 Hybrid FEM–DEM Models

To leverage the strengths of both FEM and DEM whilst minimising their respective limitations, this project develops hybrid models integrating both approaches. In these models, ballast is represented using DEM, whilst the track superstructure is modelled with FEM. This strategy allows a more realistic reproduction of the sleeper–ballast interaction and enables detailed analysis of stress transmission from the crossing to the sublayers.

Furthermore, efforts are made to improve compatibility between the two model types, which is essential for ensuring numerical stability and the reliability of the results obtained.

3 Results

The measurement campaigns conducted on operational dual-gauge turnouts provide a robust experimental database, representative of the dynamic behaviour of these infrastructures under real loading conditions. These campaigns were carried out in the through-track section of the turnout. This database serves as a basis for the validation and application of the numerical models developed in the project.

The following table summarises the recorded data corresponding to different train types and speeds over the turnout. Using this information, various analysis scenarios can be proposed to obtain results for different operating speeds and train categories.

Train type	Train type	Speed range [km/h]	Axle load [KN]
100; 106; 121; 130	High-speed train	145 – 157	225
252; 599	Commuter train	134 – 146	150
253; 256; 268; 335; 447;464; 465; 470	Freight train	29 – 127	180

Table 1: Summary of recorded data by train type.

By combining FEM and DEM, results can be generated to characterise the distribution of vertical and transverse stresses in the ballast and at the sleeper–ballast interface, to analyse the mechanisms of stress transmission to the sublayers depending on load magnitude and frequency as well as the ballast compaction state, and to determine the load levels and number of cycles required to induce ballast loosening beneath sleepers. Additionally, the study enables the identification of optimal geometric and mechanical properties defining the turnout cross-sections, with the aim of improving dynamic performance, durability, and maintainability. This is achieved through a systematic parametric study based on controlled variation of the main model parameters.

In dual-gauge turnouts, the change in track gauge along the turnout modifies the effective separation between load application points, resulting in variations in stress distribution and in the vertical and lateral stiffness of the rail–sleeper–ballast system. Consequently, the same applied load during train passage produces differentiated stiffness responses depending on the section of the turnout considered.

For this reason, characterising track stiffness as a function of gauge in mixed-gauge turnouts is fundamental to evaluating their structural behaviour, optimising design criteria, and enhancing the durability and maintainability of the infrastructure under mixed traffic conditions and varying speed regimes.

4 Conclusions and Contributions

Dual-gauge turnouts are strategic assets in networks where Iberian and standard gauge traffic must coexist, but they also represent one of the most mechanically demanding elements of the track system. Their complex rail arrangement, multiple runningsurface discontinuities, and pronounced spatial variability of support conditions promote impact-type wheel–rail interactions, uneven load transfer, and accelerated deterioration of ballast and sub-ballast. These effects are particularly relevant in dual-gauge layouts because the effective spacing and position of load application points vary along the turnout, leading to gauge-dependent stiffness and distinct dynamic responses across different sections.

This work proposes an integrated modelling approach to investigate these mechanisms by combining a computationally efficient finite element representation of the turnout superstructure with discrete element modelling of ballast. On the FEM side, the turnout is idealised using a beam–node formulation with elastic (and, when required, viscoelastic) supports, enabling full-turnout simulations whilst preserving the essential structural features governing dynamic behaviour, such as rail–sleeper interaction, local stiffness transitions, and the influence of crossing and switch regions. On the DEM side, ballast is represented at the particle scale to reproduce micromechanical phenomena that continuum ballast models cannot capture, including particle rearrangement, contact-force chain evolution, local compaction/dilation, and the onset of ballast loosening beneath sleepers.

The hybrid FEM–DEM framework provides direct access to performance indicators that are central to understanding and managing degradation in dual-gauge turnouts. These include the non-uniformity of sleeper support reactions, the distribution of vertical and lateral stresses at the sleeper–ballast interface, the propagation of stresses into the sublayers, and ballast displacement and densification patterns under dynamic loading. Importantly, the approach allows the identification of location-specific "hot spots" driven by turnout geometry and gauge transitions—areas where repeated loading is more likely to trigger differential settlement and rapid loss of track quality.

Experimental in-track measurements collected during operational traffic are used to support model calibration and validation, ensuring that the simulated responses remain representative of in-service behaviour. This linkage between numerical modelling and field data strengthens the applicability of the results and supports the use of the model as a decision-oriented tool rather than a purely academic exercise.

Overall, the proposed methodology establishes a practical basis for (i) interpreting how dual-gauge turnout geometry and stiffness variability drive ballast degradation, (ii) comparing alternative design and support configurations through parametric studies, and (iii) defining maintenance-relevant indicators associated with ballast loosening and sublayer distress. By enabling a more realistic description of turnout–sublayer interaction under dynamic loads, the framework contributes to improving durability and availability of dual-gauge turnouts, reducing corrective interventions and life-cycle costs, and supporting more resilient and interoperable railway infrastructure.

Acknowledgements

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References

[1] Mahjoubeh Sistaninia, Werner Daves, Christian Bucher, Thomas Antretter & Hans-Peter Gänser “Finite Element Investigation of the Dynamic Behavior of High-Speed Turnouts with Swing-Nose Crossing”, Lecture Notes in Mechanical Engineering, 1047-1058, 2024

[2] Sistaninia, Mahjoubeh; Daves, Werner; Bucher, Christian; Ossberger, Uwe; Estakhrouieh, Mohsen Rezaei; Antretter, Thomas; Gänser, Hans-Peter “Investigation of dynamic effects induced by wheel-rail contact in the crossing component of high-speed turnouts”, Proceedings of the Institution of Mechanical Engineers, 239 (7), 537-550, 2025.

[3] Shih, Jou-Yi; Ambur, Ramakrishnan; Dixon, Rogera, “Developing a detailed multi-body dynamic model of a turnout based on its finite element model”, Vehicle System Dynamics, 61 (3), 725-738,2023.