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A Methodology for Generating Track Models with Realistic Rail Wear for Digital Twin Applications

M. Meninas[1], A. Magno[1], J. Pagaimo[1], F. Marques[2], S. Vieira[1] and H. Magalhaes[1]

[1]IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
[2]CMEMS-UMinho, Universidade do Minho, Portugal

Abstract

Railway infrastructure managers face the continuous challenge of maintaining the rail network within strict safety and operational parameters. A critical aspect of this maintenance is ensuring that rail wear remains below the thresholds imposed by standard regulations. Traditionally, rail wear inspection relies on dedicated track recording vehicles operating on a periodic basis. However, a key challenge in modern railway engineering is the development of on-board condition monitoring technologies capable of being installed on in-service vehicles for continuous monitoring aiming to optimize maintenance costs and avoid components failure. To address this gap, this study proposes a methodology to evaluate rail wear based on the dynamic response of operational vehicles. Recognizing that vehicle dynamics are influenced by rail profile degradation, numerical simulations are employed to analyse vehicle behaviour and generate comprehensive datasets correlating dynamic responses with specific rail wear conditions. Track models incorporating varying degrees of worn rails are developed using a dedicated computational tool originally designed to support the complex geometry of switches and crossings (S&C). Furthermore, an advanced wheel-rail contact model, previously benchmarked for S&C applications, is implemented to handle the complex contact mechanics associated with worn rail profiles. Ultimately, this approach provides a robust simulated framework to support the development of continuous, data-driven track inspection strategies.

Keywords: railway dynamics, wheel-rail contact, wear, multibody dynamics, spatial interpolation, digital twins.

1 Introduction

Motivated by the high costs and low frequency of traditional track inspections, this study aims to enable continuous infrastructure monitoring using in-service commercial vehicles. By correlating rail wear with vehicle dynamics through high-fidelity multibody simulations, this work lays the foundation for scalable, cost-effective, and data-driven predictive maintenance strategies.

Many papers address the rail wear inspection through specialized inspection vehicles, such as an optical measurement system that in real time details the rail profile with lasers and compares the cross-section profile with the obtained profile and determines the rail wear [1]. Coccia *et al* proposes non-contact ultrasonic guided waves to test for rail defects, the laser and air coupled sensors work as one, the first emits a laser pulse and the second receives the guided ultrasonic wave. The anomalies are detected by the change in the wave trajectory, this system is reliable for transverse defects, under-shelling, vertical and horizontal split heads but is limited to very low speeds and is only tested in artificial defects which may create higher accuracy. Zhang *et al* reviews the many methods to identify wheel burns which are increasingly more relevant in China because of high-speed incorporating ultramagnetic testing, acoustic emission testing, active infrared thermography [2]. A similar approach using lasers and a high-resolution camera that moves stepwise by a microcontroller, the result of the measurements is the spatial arrangement of points of the frog surface. They plot the trajectory which is how the wheels centre moves up and down rolling across the frog. This proposal by Kovalchuk *et al* allows for a high detection of defects but is limited to frogs and specifically this frog [3].

Track foundation, track irregularities, and rail wear significantly influence vehicle dynamics through the forces generated at the wheel-rail interface [4], [5], [6]. To assess these effects, multibody simulation is a vital tool, as it incorporates the equations of motion while accounting for essential vehicle properties, such as the inertia of the main bodies and the characteristics of mechanical components, such as bearings, traction rods, springs, and dampers. However, performing multibody simulations on tracks with varying rail wear profiles is challenging. Current software packages are highly sensitive to the quality of rail surface input data [7], [8]. Most of these tools require a set of profiles that must be accurately interpolated to describe the rail surface topology effectively [7], [9]. Note that the typical wheel rail contact forces are around tens of kN leading to wheel-rail interference that are around tens of µm [10]. Therefore, a small overshoot in the interpolation of the variable rail surfaces might lead to unrealistically high contact forces and, potentially, to a high contact pressure that would lead to plastic deformation, which violates the majority of the wheel-rail contact models that covers only the elastic regime. Although the plastic deformation has been proposed in the wheel-rail contact model proposed in [11], [12], updating the wheel and rail geometry leads to a complex task that has not been addressed yet.

The remainder of this paper is organized as follows: Chapter 2 presents the methodology, including a brief description of the computational tool used to create track models with worn rails, as well as the wheel-rail contact model utilized to compute the vehicle-track interaction. Chapter 3 provides a detailed analysis of the quality of the rail surface models through the first and second derivatives, which play a crucial role on the performance of the vehicle-track interaction analysis. Finally, the conclusions and future work are outlined in Chapter 4.

2 Methods

The methodology implemented in this work focuses on identifying typical rail wear, characterized by surface variations of the rail head and creating track models with worn rails. The variable wear along the rail influences the wheel-rail interaction and, consequently, the vehicle dynamic behaviour.

The Union Internationale des Chemins de fer (UIC) 712 is used to identify the most common rail head defects and consequently define them quantitatively, to assemble a system that can detect when the defect is above the imposed threshold. Representatives rail defects are the short and long pitch corrugation, side wear and squats as illustrated in Figure 1.

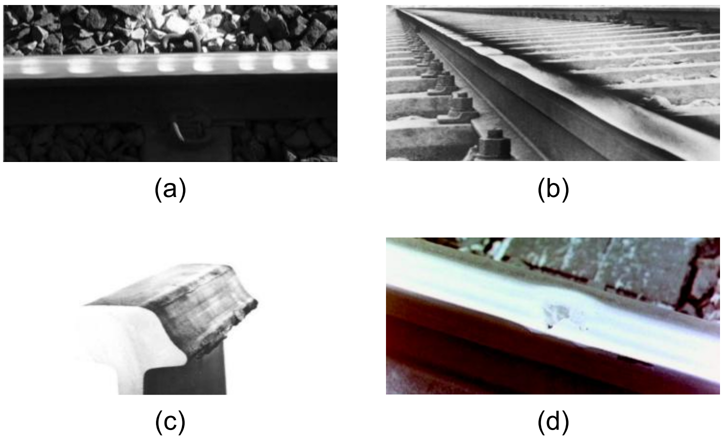

Figure 1: Rail defects (a) short pitch corrugation; (b) long pitch corrugation; (c) side wear (d) squat.

The parameterization of the rail surface where the wheel is prone to contacting the rail is required for the multibody simulation. All multibody codes require a set of rail cross sections obtained along the rail component, enabling its three-dimensional interpolation, where the challenge is that the interpolation of the surface is representative of the worn rail [13]. Here, a brief description of the modelling approach is described based on the schematic representation of the methodology depicted in Figure 2, which is used in several multibody codes, like VI-Rail, SIMPACK and MUBODyn.

The development of track models with variable rail wear leverages a computational tool originally designed for Switches and Crossings (S&C). The rail profiles are returned from this tool through Boolean operations extrusion and cutting, analogous to those used in 3D CAD modelling. The process involves three primary steps: projecting profiles at specified longitudinal coordinates; smoothing sharp edges to simulate manual grinding; and creating longitudinal section breaks to facilitate the surface interpolation required for complex geometries, such as crossing rails. These operations utilize defined profiles and paths, as illustrated in Figure 3(a) and Figure 3(b) for extrusion and cutting, respectively, while Figure 3(c) displays the selected rail profiles used for surface interpolation.

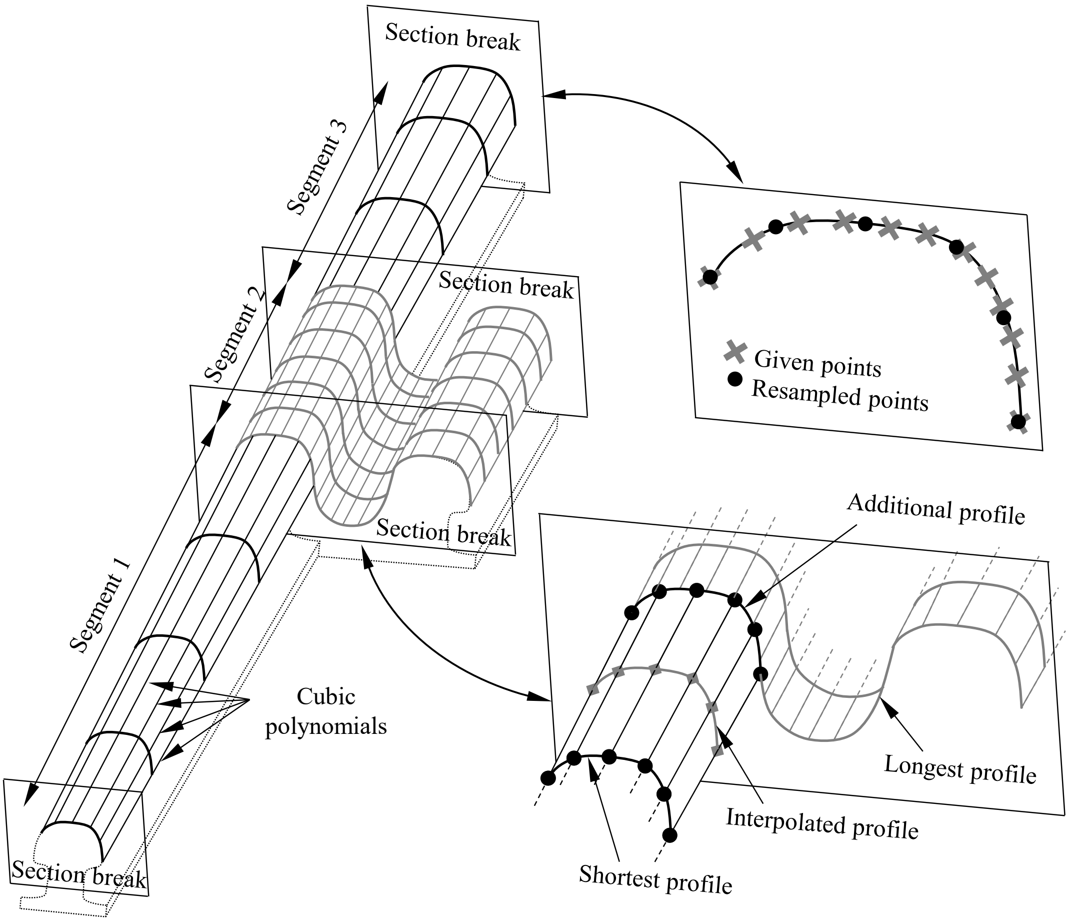

Figure 2: Rail surface parameterization (adapted from [8])

3 Results

The S&C design tool is utilized to replicate the typical rail wear patterns specified in the UIC 712 standard, as illustrated in Figure 1. A series of track models is developed by modelling the rail surface through an interpolation of rail profiles. These profiles are generated with the extrusion of the nominal rail geometry combined with custom cutting tools and defined paths, enabling the accurate representation of various rail wear types at different levels of severity.

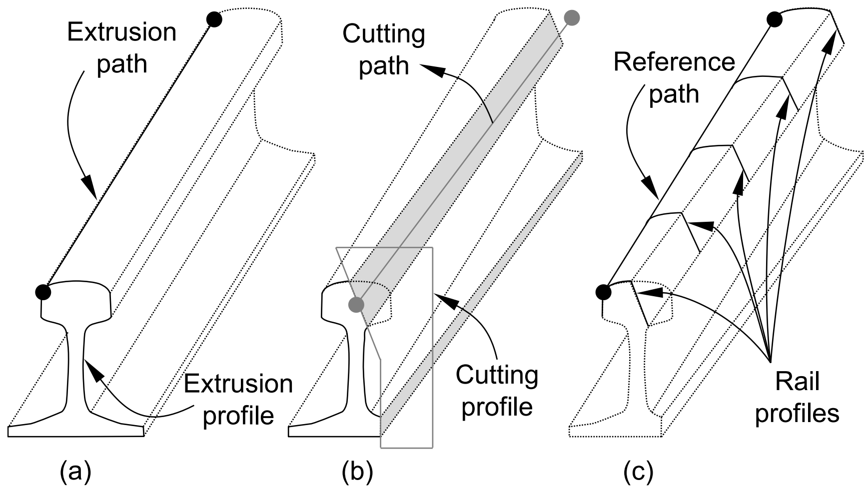

Figure 3: (a) Rail extrusion, (b) cutting of the rail and (c) resulting profiles for the track model.

Since the quality of rail surface interpolation depends heavily on profile refinement, specifically the number of points per profile and the density of profiles along the track arc length, the first and second derivatives are analysed across the rail surface. **Error! Reference source not found.** displays the lateral first and second derivatives for the rail models representing the wear types illustrated in Figure 1, allowing for an assessment of the interpolation quality that will ultimately influence the vehicle-track interaction analysis.

4 Conclusions and Contributions

This paper proposes a methodology to generate large sets of realistic track models for vehicle-track interaction analysis. These models enable the creation of enriched databases, facilitating big data approaches to correlate rail wear conditions with vehicle dynamics. Ultimately, this work aims to contribute to the development of condition monitoring systems that predict rail wear life. By utilizing instrumented in-service vehicles, this approach allows for daily, continuous track monitoring as an alternative to traditional periodic inspections.

The developed track models are analysed from a geometric perspective, with particular attention to the first and second derivatives, which are critical for the computational efficiency of numerical simulations. Key parameters, such as the number of profiles and the severity of wear, are explored to determine their impact on the surface modelling of worn rails. This analysis is of great importance for the subsequent multibody simulations, where vehicle dynamics and wheel-rail interaction forces will be evaluated in detail.

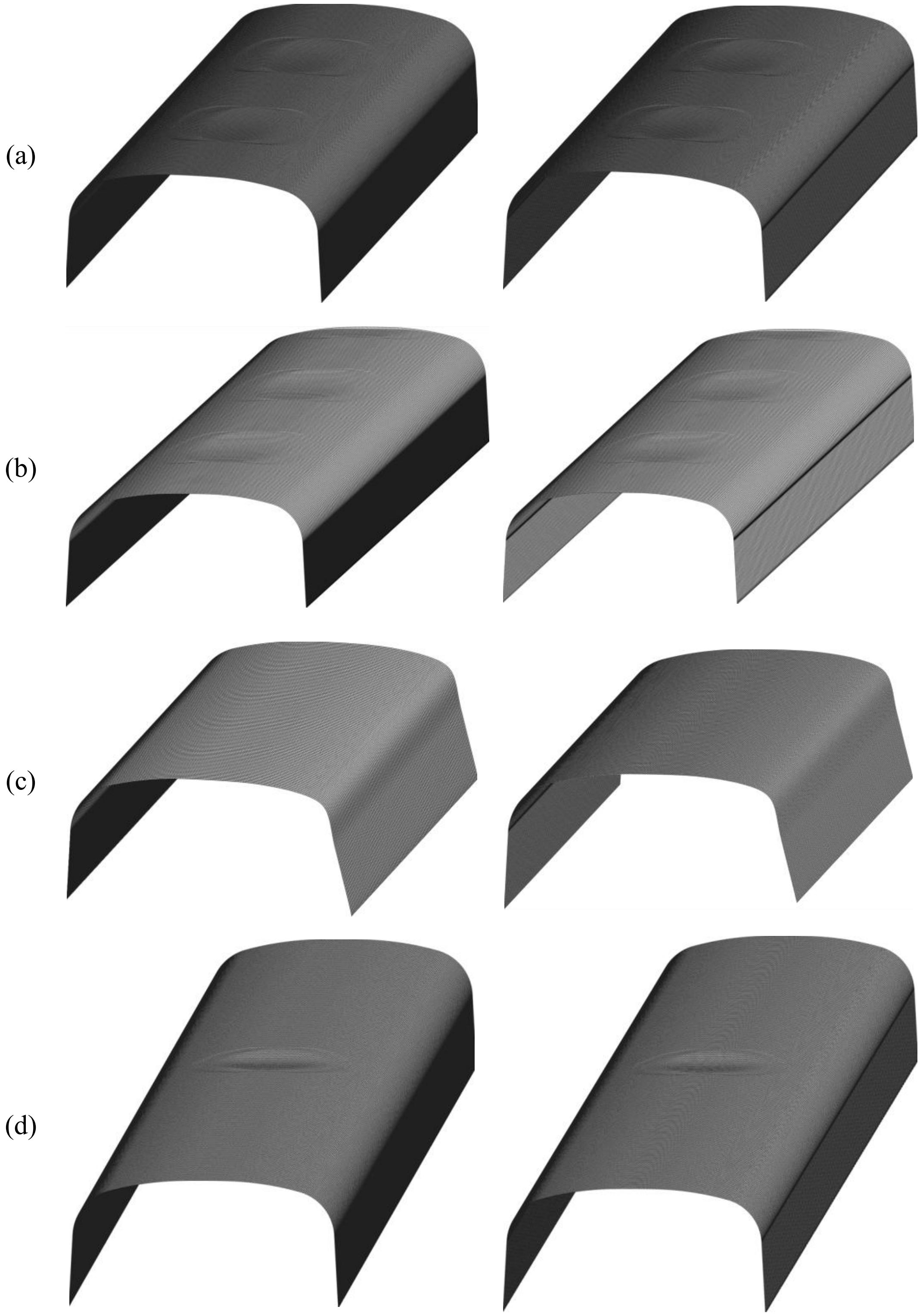

Figure 4: Lateral first and second derivatives of the rail surface for various wear types: (a) short pitch corrugation; (b) long pitch corrugation; (c) side wear (d) squat.

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