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**HYBRID NUMERICAL-ANALYTICAL APPROACH FOR PREDICTING THE
VERTICAL LEVELLING LOSS OF TRACK GEOMETRY IN A HEAVY-HAUL
RAILWAY**

BY

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DOCTOR OF PHILOSOPHY**

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ABSTRACT

Post-construction track geometry deterioration is one of the major problems for railway track maintenance. Increasing train velocities, frequencies of railway transport, and axle loads can accelerate rapidly this deterioration due to repeated traffic loadings. Technically, this trend requires higher standards not only for each individual track component but also for the track geometry. An important contribution to the track geometrical deterioration is the ballast settlement, which impacts on the track geometry, specifically on one of the most important track geometrical parameters: the vertical levelling (VL). Any weakness in the railway track support sub-system will affect negatively the railway track vertical profile. It means inferior ride comfort quality and excessive dynamic forces for railway track and vehicles components, resulting inevitably in a less attractive and safe railway. Track geometrical vertical levelling loss (VLL) is defined as a parameter of how much the rail loses its vertical position in the track physical space. The track conditions (smooth, unsupported-sleeper, and uneven tracks) plays a significant role in accelerating the VLL.

With an emphasis on the combined degradation of railway track geometric elements and components, an innovative hybrid numerical-analytical approach is proposed for predicting the VLL. In contrast to previous studies, this research unprecedentedly considers the effect of unsupported sleepers (US) and the influence of initial track irregularities (ITI) on VLL under cyclic loadings, elastic-plastic behaviour, and different operational dynamic conditions. The nonlinear numerical models are simulated using an explicit finite element (FE) package, and their results are validated by experimental data. The outcomes are iteratively regressed by an analytical logarithmic function that cumulates permanent settlements, which innovatively extends the effect of track condition on VLL in a long-term behaviour. Additionally, a power

function factor innovatively extends the response of US on VLL over a long term. New findings reveal that this innovative numerical-analytical approach can very well predict the VLL long-term performance considering not only the number of cycles or MGT but also different dynamic conditions to support the development of a specification to proceed the investigation of track geometrical degradation. This approach can also support more complex analysis of track geometry elements with a minimal need of carrying out expensive field experiments. Moreover, the proposed methodology can accurately predict both the effect of US and the influence of initial track irregularities on the track geometrical VLL considering different railway operational conditions (and configurations). Finally, this hybrid numerical-analytical approach can be applied to enhance the development of new practical maintenance and construction guidelines to support the maintenance activities in a heavy-haul ballasted railway track for a minimum effect on VLL extending the railway track service life.

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CONTENDS LISTINGS

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LIST OF PUBLICATIONS

This doctoral research thesis is written in the format of collection of articles predominantly constituted of the following key scientific articles:

Journal papers:

Melo, A. L. O. de, Kaewunruen, S., Papaelias, M., Bernucci, L. L. B., and Motta, R. (2020). Methods to monitor and evaluate the deterioration of track and its components in a railway in-service: a systemic review. *Frontiers in Built Environment – Transportation and Transit Systems*, Vol. 6.

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Melo, A. L. O. de, Kaewunruen, S., Papaelias, M. (2023a). Effect of unsupported sleepers on vertical levelling loss of heavy-haul railway track geometry under cyclic loadings. *Proc IMechE, Part F: J Rail and Rapid Transit*. [under review]

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CHAPTER 1

INTRODUCTION

This chapter introduces the doctoral research thesis and presents the background/motivation of the research to guide the readers to understand in-depth the current issues. Scope of work and aim and objectives are also introduced. Lastly, the thesis structure is presented to describe how this thesis is organized.

1.1. Background and Motivation

At present, heavy-haul railway systems play a significant role in modern railway transportation systems by efficiently transporting large amount of iron ore, coal, soybean, and other commodities products. Because of the increased demand of those railway cargoes, the system has attracted further investments not only to increase in capacity but also to improve the railway track infrastructure quality, which in fact characterizes this as a valuable asset worldwide (Ngamkhanong 2020). As the use of railway track infrastructure has also increased, it can be the main reason of failure of track components and its geometry.

Post-construction degradation of track geometry in a heavy-haul ballasted railway track is one of the major issues for track maintenance (Melo et al. 2022). Increasing demands for higher velocities, heavier axle loads, and more frequent rail transport can accelerate rapidly this degradation due to cyclic traffic loadings (Nielsen and Li 2018). An important contribution to this degradation is the differential track settlement, which impacts directly on the spatial position of the rail track, defined as vertical levelling that is one of the most important track geometry parameters. It has been reported that vertical profile defects represent more than 50%

of track geometric irregularities in a ballasted railway track (Soleimanmeigouni et al. 2018). A poor vertical profile means a poor ride quality and excessive dynamic forces for track and vehicles components, and the inevitable result is a less efficient, less popular and more costly railway (Thom and Oakley 2006). In the railway section where the vertical profile exceeds the limit, the railway train velocity needs to be restricted to reduce the risk of derailment. The train velocity restriction is usually applied until the track recover its track geometry causing train delays and disruptions. Figure 1.0-1 shows vertical profile defects in a typical heavy-haul ballasted railway track.

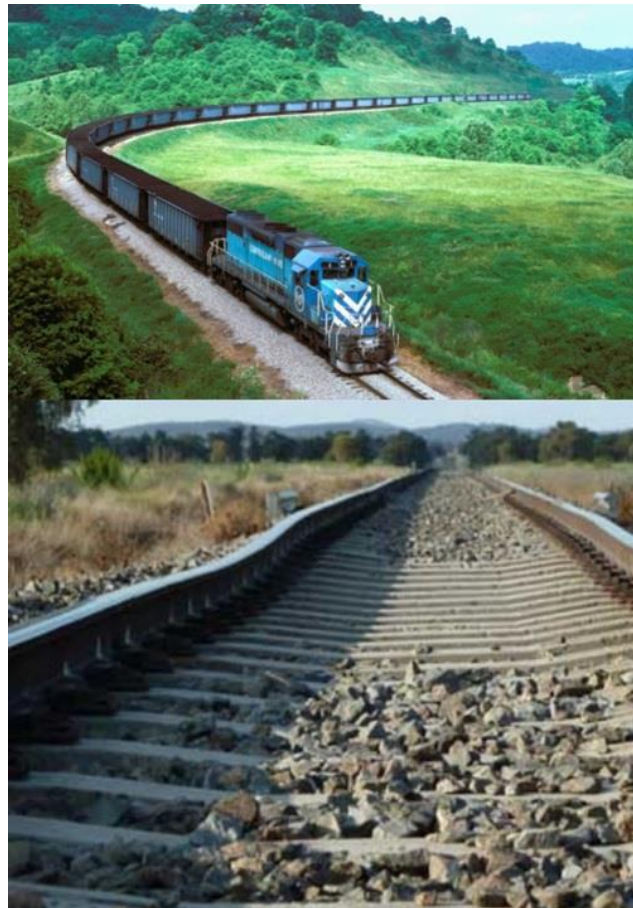


Figure 1.0-1. Vertical profile degradation in a typical heavy-haul ballasted railway track (modified from Soleimanmeigouni et al. 2018).

The mechanism governing the heavy-haul ballasted railway track geometrical degradation is a complex process involving diverse parameters such as train velocities, axle loads, track and vehicle characteristics, maintenance processes, and environment (Ferreira and Murray 1997, Esveld 2001, Lichtberger 2011, Berawi 2013). It has been recognised as the main source of the need for track maintenance, particularly due to the settlement of the railway substructure in which the railway ballast is the most critical component as it is the only external constraint applied to the ballasted railway track to restrain it (Lim 2004). Figure 1.0-2 illustrates a typical vertical profile of ballasted railway track of the relative contributions of railway substructure components on track settlements under railway traffic assuming a good foundation (Selig and Waters 1994).

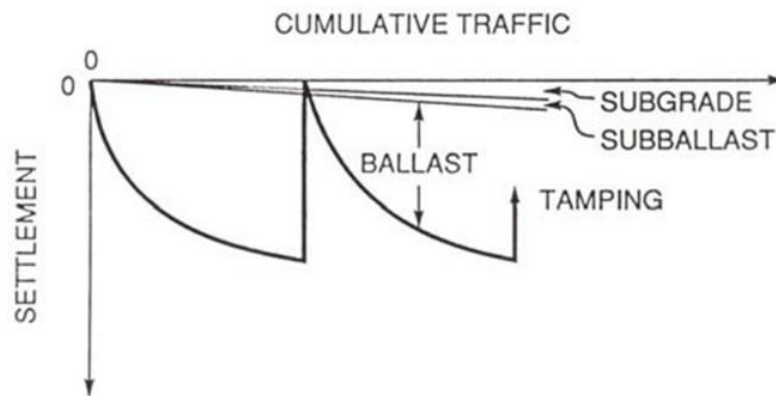


Figure 1.0-2. Typical vertical profile of ballasted railway track of the relative contributions of railway substructure components on track settlements under railway traffic assuming a good subgrade (Selig and Waters 1994).

The VLL in a heavy-haul ballasted railway track can be reduced by a proper compaction and stabilization of the ballast bed before running the first trains. In turn, as railway ballast is the main source of track settlements, ballast deterioration leads to insufficient support for maintaining track vertical profile geometric element even if the railway ballast be well-compacted. In fact, due the rearrangement of the ballast stones to reach a state of equilibrium, particle breakdowns due to the impact loads or outside contamination, such as penetration of sub ballast and subgrade into ballast voids or iron ore fines, the ballast experiences a great permanent deformation (Hay 1982, Profillidis 2006, Indraratna et al. 2011, Nielsen and Li 2018, Ngamkhanong 2020, and Melo et al. 2022).

Many researchers have dedicated to study the vertical profile degradation for the last 4 decades applying different approaches (empirical, mechanist, and empirical mechanist) for predicting the evolution over time of vertical profile geometric element to proactively identify whether it fails to maintain its known standard characteristics (Melo et al. 2020). Mostly studies in the past have investigated this phenomenon using empirical approach to obtain the railway track vertical profile loss (VLL) through statistical track quality indices in specific railway sites. Few other studies have investigated the VLL applying a mechanist or empirical-mechanist approaches. In these few cases, different methods have been applied for qualifying the VLL through field/laboratory experiments and numerical analysis (Finite Element Method – FEM). However, none of the researchers have accurately investigated the quantitative dynamic VLL under cyclic loadings and elastic-plastic behaviour of material (e.g., railway ballast cumulative deformation) taking into account different track conditions such as smooth track (no track geometric irregularities), unsupported-sleeper track (hanging sleepers), and uneven track (track with vertical profile geometric element defects). It is crucial to investigate these effects on heavy-haul ballasted railway tracks as those findings can support the track engineers to define

properly the VLL thresholds, develop better practical maintenance guidelines, and enhance the maintenance activities to extend the railway track service life. In fact, a harmonized and coordinated methodology that is easy to follow and apply can significantly improve the railway industry practice as it can be used not only to maintenance planning and decision-making proposes, but also to support the development of new track/vehicle components estimating their life cycle and behaviour in different railway operational conditions.

In this study, a nonlinear numerical modelling has been proposed to predict the train–track interactions validated by experimental data, and later an analytical method has been integrated to estimate VLL, under heavy-haul dynamic cyclic loadings, which can also embrace the train–track dynamics under different track conditions (smooth, unsupported-sleeper, and uneven tracks). It is important to note that previous studies related to smooth tracks are limited to a dependency on the number of cycles or million gross tonnes (MGT) and cannot be generalized (Melo et al. 2022). On this ground, this study further embraces the influence of dynamic and operational conditions, track components and vehicle parameters. Accordingly, short- and long-term behaviours of a ballasted track can be analysed to determine parametric effects on VLL in smooth tracks. Additionally, analytical methods are also applied iteratively to identify an innovative function factor outlining the effect of unsupported sleepers (US) on VLL under heavy-haul cyclic loadings (Melo et al. 2023a). Therefore, a long-term performance of ballasted railway track can also be evaluated to determine parametric responses of US on VLL. In general, as described above, no other studies have provided accurate and parametric investigation of the effect of initial track irregularities (uneven track) on VLL considering the train-track interaction as a whole and: (1) long-term performance, (2) operational conditions (e.g. axle load, train velocity), (3) vehicle parameters (e.g. dynamic stiffness of 1st suspension), and (4) track parameters (e.g., dynamic elastic-plastic behaviour of railway ballast). On this

ground, to predict properly the dynamic influence of initial geometric defects on VLL under cyclic loadings and elastic-plastic behavior of railway ballast tracks, this research also proposes the development of an innovative nonlinear numerical-analytical method to predict track geometrical VLL considering not only the transient dynamic conditions but also the long-term effect of ITI under repetitive loading cycles over the service life (Melo et al. 2023b). With the increase in computing power and speed, it will be possible to adopt a more complex model of track geometry elements incorporating a diverse dynamic railway environment (Ngamkhanong et al. 2019, and Melo et al. 2022). From an engineering perspective, this can enhance predictive maintenance for both track geometry degradation and component deterioration and support the development of an efficient practical maintenance guideline recommending US and ITI thresholds for minimum effect on VLL. Figure 1.0-3 illustrates schematically the nonlinear numerical-analytical approach proposed in this study.

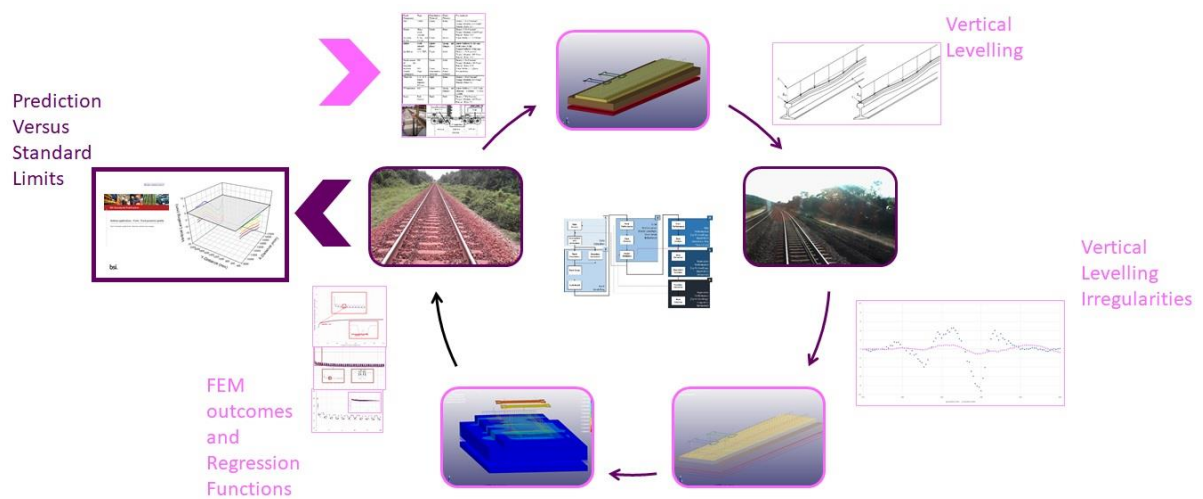


Figure 1.0-3. Nonlinear numerical-analytical approach proposed in this study.

1.2. Scope and Limitations

This research primarily focuses on investigating the phenomenon of track geometrical degradation related to vertical profile geometric element in heavy-haul ballasted railways using numerical-analytical approach (FEM and regression performance). Heavy-haul railways are defined as those railways with a minimum 25-tonnes axle load and a maximum 100-km/h train velocity of new, upgraded, or existing lines. Firstly, this research reviews the modelling procedures for a smooth ballasted railway track for vertical displacements (monotonic loading and elastic behaviour of materials).

After reviewing the previous model, it was found suitable for the VLL analysis as it could help to provide a realistic model and reduce the computational time of simulation in High Performance Computer (HPC), particularly as the simulation requires several cyclic loadings to conclude the performance. The simulation of smooth tracks is conducted using the LS-Dyna FE package, a commercial software.

It is important to note that this research focuses on the numerical simulation and regression performance of the VLL of heavy-haul ballasted railway track under cyclic loadings and elastic-plastic behaviour of track components (railway ballast) as the experimental results data have hardly been reported and are limited due to require heavy facilities and full-scale railway tracks. Therefore, in this research, the numerical results were first validated against the previous experimental results whose operational condition was under monotonic loading and track/vehicle components parameters followed elastic law of materials. The parametric studies are conducted using nonlinear analyses to evaluate the major factor influencing of railway operational conditions (axle load and train velocity), track/vehicle components parameters, and track conditions (smooth, unsupported-sleeper, and uneven tracks) on the VLL phenomenon, as aforementioned. Regarding data collection process, mostly datasets have been obtained from

a heavy-haul railway in Brazil and they are related to track/vehicle parameters, and track geometric elements measured/recorded by EM-100 Recording Car (RC) between 2018 and 2020.

1.3. Aim and Objectives

This research aims to develop a hybrid numerical-analytical approach to predict track geometrical degradation in a heavy-haul ballasted railway track under cyclic loadings to support the understanding of the effect of different railway operational conditions, track/vehicle parameters, and track conditions on vertical profile loss (VLL). The aim of this research is achieved by the objectives as follows:

- Review the key concepts of heavy-haul ballasted railway systems (track, vehicle, forces acting on/in, wheel-rail interactions, and vehicle/track models).
- Identify critical parameters and track conditions affecting the track geometrical degradation.
- Review the ballasted railway track geometrical degradation models considering different track conditions (smooth, unsupported-sleeper, and uneven tracks).
- Investigate the vertical profile loss (VLL) phenomenon in a ballasted railway track subjected to heavy-haul axle load using the numerical-analytical approach (FEM and regression performance) considering different railway operational conditions (e.g., train velocity) and track/vehicle parameters (e.g., ballast cumulative deformation).
- Analyse the effect of unsupported sleepers (US) on VLL, considering different axle loads and US configurations, to help define thresholds of US configurations for a minimum effect on VLL.

- Analyse the influence of initial track irregularities on VLL in a ballasted railway track subjected to heavy-haul axle loads considering different railway operational conditions (e.g., train velocity, axle load), and sets of initial track irregularities – ITI (e.g., Standard Deviation – SD of vertical profile) to identify an acceptable condition (thresholds) of ITI that can be defined for a minimum effect on VLL.

1.4. Thesis Structure

This doctoral thesis consists of eight chapters, including introduction and conclusion/recommendations. Figure 1.0-4 illustrates the thesis structure and helps readers clearly understand the outcomes of the study. This doctoral thesis is written in the format of a collection of articles collection (also called a ‘compilation thesis’) being formatted according to the ‘alternative format thesis guidelines’ based on the University of Birmingham’s regulation 7.4.1.

Following the introductory chapter, Chapter 2 presents a literature review regarding a ballasted railway system. The main concept of railway track/vehicle distinguishing their key components/elements are presented as well as railway vehicle-track interaction mechanisms and different methodologies to model a ballasted railway vehicle-track system. In addition, Chapter 3 presents a critical and an extended literature review about railway track geometrical degradation considering three different track conditions (smooth, unsupported-sleeper, and uneven tracks) that influence on vertical profile loss (VLL). Also, this chapter presents the concepts of each mapped track condition and briefly describes the different methodologies applied to predict track geometrical degradation over different railway track conditions.

Chapter 4 presents a general methodology to carry out this research. Also, it presents three innovative and complementary methodologies to predict vertical levelling loss (VLL)

over different railway track conditions: smooth track (no track geometric irregularities), unsupported sleepers track (hanging sleepers), and uneven track (track with geometric irregularities). The first methodology related to smooth tracks will be the reference to the others. The results of application of those proposal methodologies are respectively discussed in Chapter 5, 6 and 7, to investigate the influence of the track conditions.

As mentioned before, Chapter 5, 6, and 7 present and discuss the outcomes of an innovative numerical-analytical approach applied to, respectively, predict the VLL on smooth tracks, analyze the effect of unsupported-sleeper tracks on VLL, and exam the influence of initial track irregularities (ITI) also on VLL. These chapters discuss the results obtained from numerical simulation and regression performance of VLL in a heavy-haul railway in Brazil. Additionally, these chapters present parametric approaches to extend the study of the effect of different railway dynamic conditions on VLL. Each individual chapter contains in-depth analysis of different heavy-haul ballasted railway track conditions benefiting readers by clearly understanding the influence of them on VLL. Finally, Chapter 8 presents the conclusion of this thesis and the recommendations for future research.

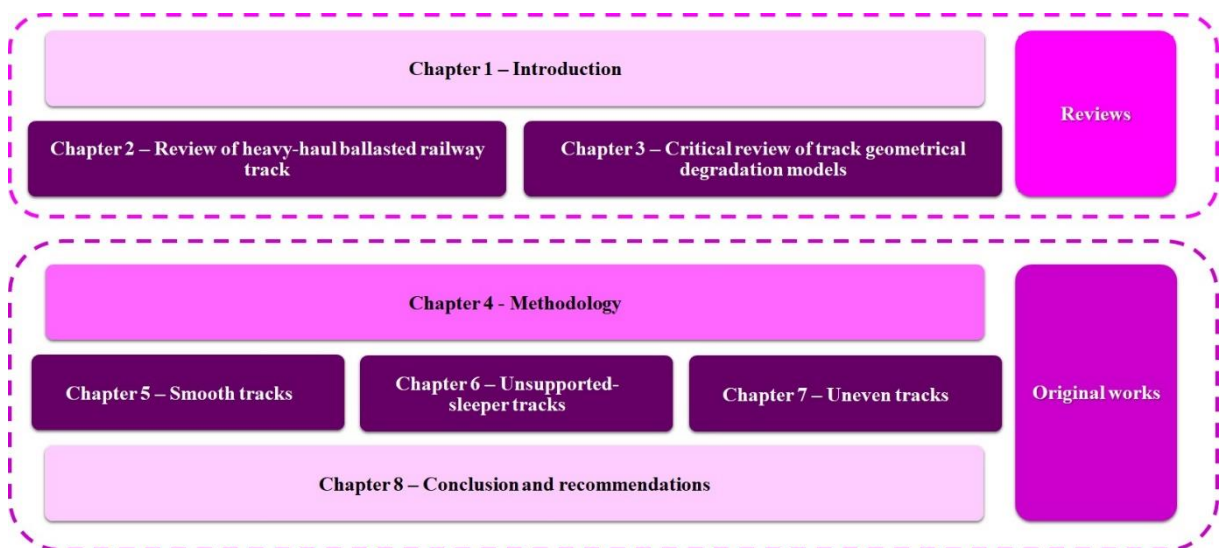


Figure 1.0-4. Thesis structure.

1.5. Summary

Nowadays, post-construction track geometry degradation is one of the major problems for railway track maintenance. Increasing train velocities, frequencies of railway transport, and axle loads can accelerate further rapidly this degradation due to repeated traffic loadings, which requires higher standards not only for each individual track component but also for the track geometry. Over 50% of track geometric irregularities in a ballasted railway track are related to vertical profile meaning a poor ride quality and excessive dynamic forces for track and vehicles components in a vicious cycle. Limited number of studies have investigated this phenomenon and this research proposes an innovative numerical-analytical approach to predict the effect of different railway operational conditions, track/vehicle parameters, and track conditions (smooth, unsupported-sleeper, and uneven tracks).

Chapter 1 gives an overview about background/motivation of this research on a track service life perspective. This chapter also points out the scope of work (and limitations) to afterward defining the aim and the objectives to achieve the goal. Next chapter (Chapter 2) will describe the key concepts related to ballasted railway track.

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CHAPTER 2

A REVIEW OF BALLASTED RAILWAY TRACK

This chapter has been written to describe the main concept of a railway track distinguishing its key track components and geometrical elements. Also, it describes the railway vehicle-track interaction mechanisms and the heavy-haul unpowered vehicle (wagon) components. Moreover, it describes the forces that usually act on a track influencing particularly the track geometrical degradation and explains the general railway operational conditions. Finally, this chapter presents and discusses the different methodologies to model a ballasted railway vehicle-track system.

2.1. Railway Track

The objective of a railway track is to allow railway vehicles to be guided without risk of derailment, ensuring a high degree of passenger comfort and/or a low degree of freight damage (Lichtberger 2011, Tzanakakis 2013, and Melo et al. 2020). It consists of many parts, which can be viewed as a railway sub-system or as individual components.

A modern railway track can be classified in two types: ballasted railway track (conventional) and non-ballasted railway track (also known as “slab track” or “ballastless track”). Ballasted railway track has been used worldwide for conventional train speed up to 200 km/h (Profillidis 2006), whereas ballastless railway tracks have been used rationally for high-speed railways (train velocity > 200 km/h) due its advantages – when compared to that ballasted track – for lower deformation, higher stability, and lower maintenance cost (Ngamkhanong 2020).

Despite the advantages of slab railway tracks, ballasted tracks continue being used massively around the world as it provides lower construction cost than non-ballasted tracks. Besides, ballasted railway tracks ensure a certain degree of flexibility, which is an essential characteristic in the event of differential settlements. It is important to note that ballasted railway tracks tend to lose faster its initial geometry due to those occurrences (differential settlements) under heavy-haul axle loads compared to ballastless tracks, which requires frequent maintenance activities due to higher rate of track geometrical degradation. Thus, ballasted railway tracks will be considered in this research. Figure 2.0-1 shows typical ballasted and ballastless railway track.



Figure 2.0-1. Typical ballasted (left) and ballastless (right) railway track cross sections.

2.2. Ballasted Railway Track and its Components

Ballasted railway track is the conventional railway track used around the World. It consists of two main parts: superstructure and substructure. The most visible part of the main line track composed of rail, fastening system, sleeper and ballast is referred to superstructure, whereas substructure is associated with a geotechnical system composed of sub ballast, reinforcement of subgrade, and subgrade (formation).

Both superstructure and substructure are mutually important to ensure the safety and comfort of passengers and quality of travel (Kaewunruen and Remennikov 2008) and the preservation of freight (Melo et al. 2020). The first one supports and distributes the train loads and is subjected to periodic maintenance and replacement. The second (substructure) is the one in which the train loads are transferred after proper distribution in the superstructure. In principle, the substructure should not be subjected to interventions during periodic maintenance (Profillids 2006). Figure 2.0-2 illustrates a typical straight segment of ballasted railway track and key track components.

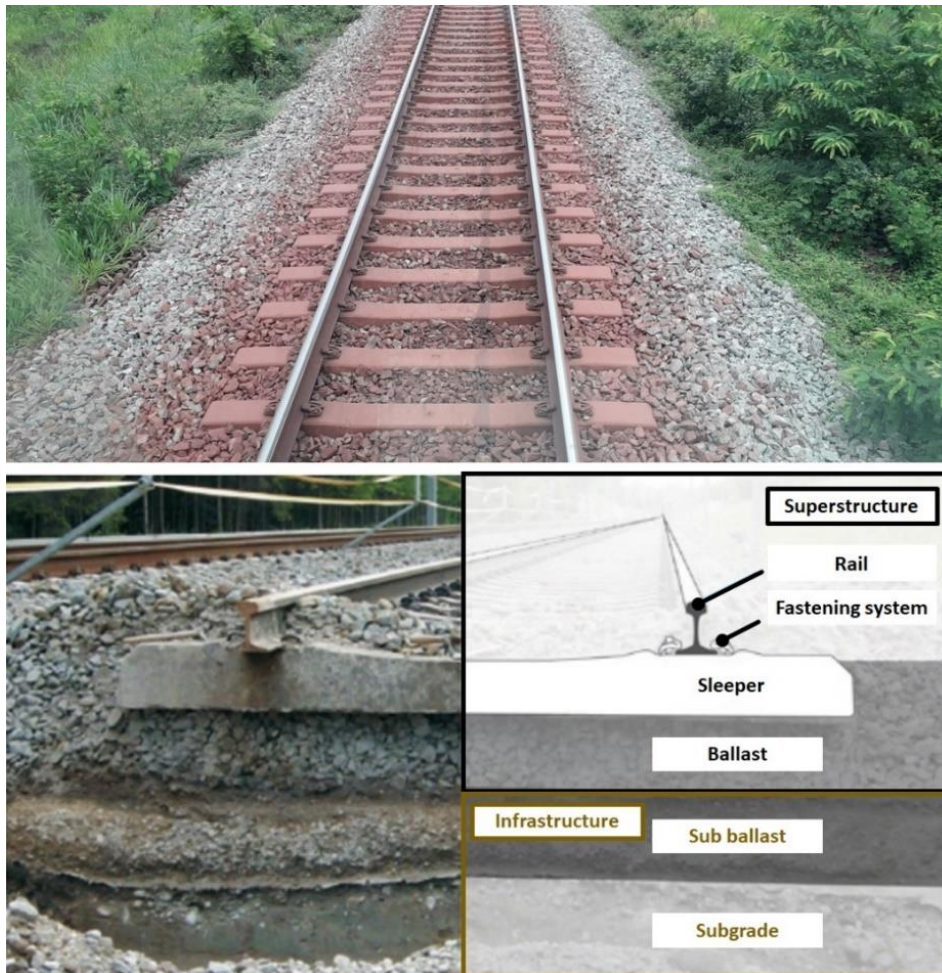


Figure 2.0-2. A typical straight segment of heavy-haul ballasted railway track (top) and key track components (bottom).

2.2.1. Rail

Rail is the longitudinal member of a railway track used to guide and support the vehicle's wheels and transfer vehicle's wheel loads to the beneath components. It is a rolled steel beam modified geometrically and metallurgically to provide high resistance to wear, compressive forces, and fatigue (Hay 1982, and Lichtberger 2011). Also, rail must meet other requirements such as high yield strength, tensile strength and hardness, good weldability, good surface quality, evenness, and consistent cross section (Lichtberger 2011). Rail is considered as a continuously and elastically supported flexible beam deflecting under load with the load distributed over 9-11 sleepers (Hay, 1982). The stiffness or resistance to bending varies as the moment of inertia of its cross section (Melo et al. 2019). Figure 2.0-3 illustrates the wave action in loaded rail and in detail, a flat-bottomed rail cross section of ballasted railway track.

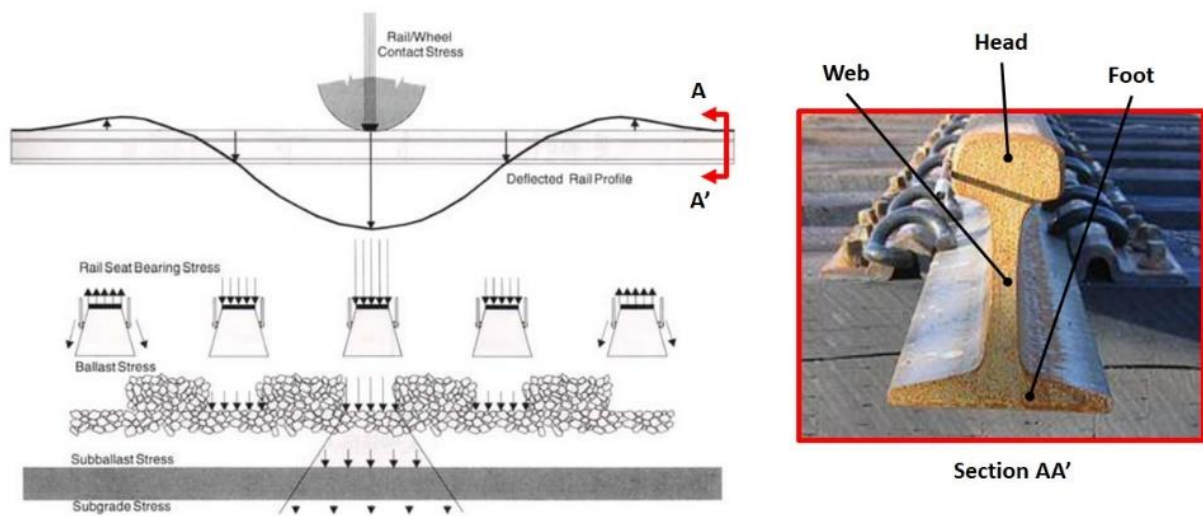


Figure 2.0-3. The wave action in loaded rail (Selig and Waters 1994) and, in details, a flat-bottomed rail cross section of ballasted railway track (PWI 2017).

2.2.2. Fastening system

The purpose of a fastening system is to maintain the railway track gauge (distance between the two rails) and to transmit forces acting on and in the rails to the sleepers (Lichtberger 2011). As the fastening system must offer enough resistance in a vertical direction for movements upwards as well as downwards, the properties of the fastening system must be considered when the rail is exposed to vertical movement under cyclic loadings (Melo et al. 2019). Also, as pointed out by Lichtberger (2011), each pair of rails fastening system must be able to support the weight of the sleeper and the respective rail section without deformation. It is important to highlight that rail pad has an essential role as part of an elastic fastening system. The rail pad is an elastic resilient material installed on rail seats between rail and sleeper, and responsible to transfer in an attenuate manner the rail load to the sleeper while filtering out the high frequency force components (Profillidis 2006). Figure 2.0-4 illustrates an example of rail pad usually applied in a railway track fastening system.

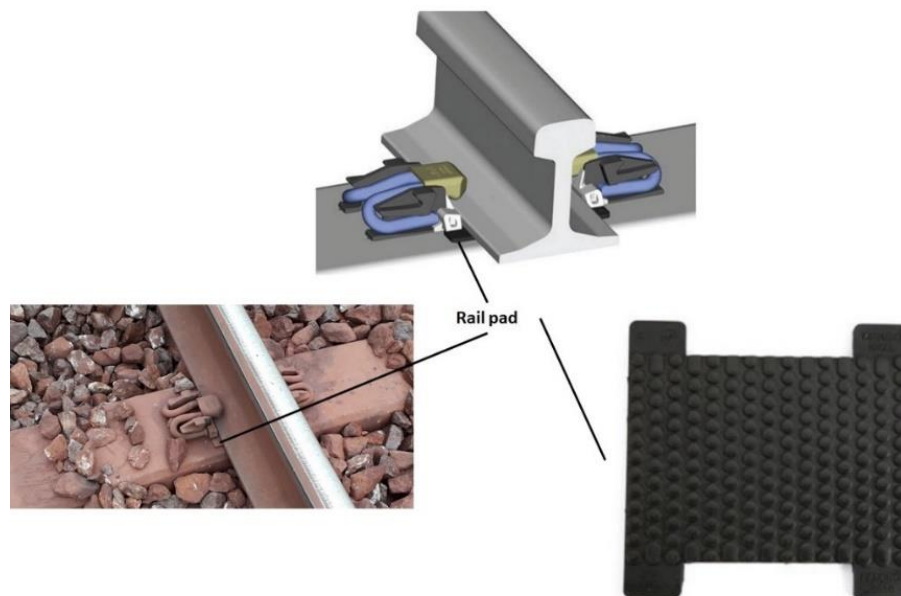


Figure 2.0-4. Example of rail pad usually applied in a railway track fastening system

(modified from Lichtberger 2011 and Tzanakaki 2013).

2.2.4. Sleeper

Sleepers are the transversal beam components of a railway ballasted track. They are the railway track components positioned between rails and ballast (Profillidis 2006, and Melo et al. 2019), which have the function of securing transversely the rails and holding them to correct gauge, transmitting the axle loads with diminished unit pressure to the ballast, and anchoring the railway track against lateral, longitudinal, and vertical movement (Hay 1982, Sengsri et al. 2020a, and Sengsri et al. 2020b). Figure 2.0-4 illustrates a typical monoblock concrete sleeper of heavy-haul ballasted railway track.

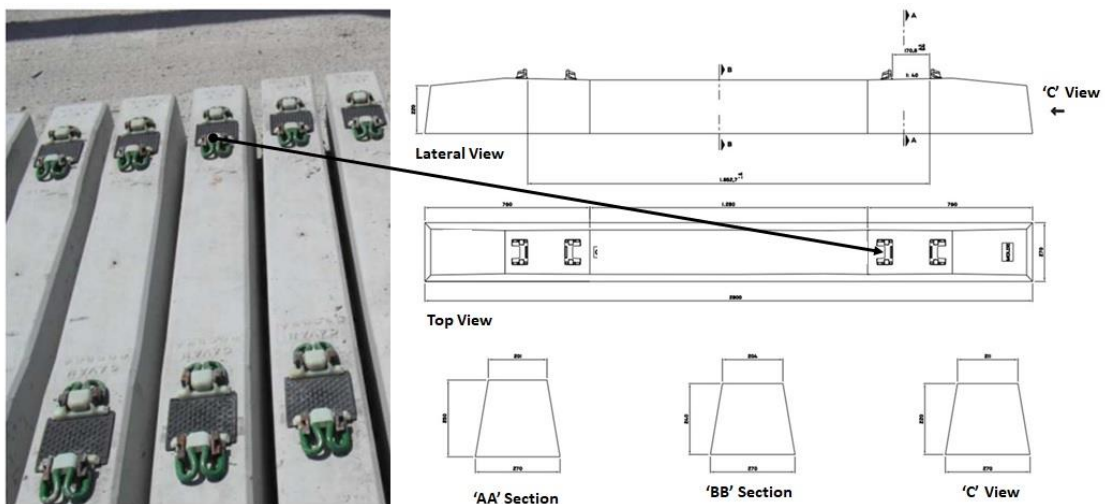


Figure 2.0-4. Typical monoblock concrete sleeper of heavy-haul ballasted railway track.

2.2.5. Ballast

Ballast is also one of the longitudinal components of a railway ballasted track considered continuous and homogeneous, and placed beneath the railway track structure (rails, fastening system, and sleepers) and above the sub ballast (capping) (Sun et al. 2016). It is denoted as the layer of crushed rocks (stones) on which the sleepers rest (Profillidis 2006). Moreover,

according to Guo et al. (2022), the ballast fills the space between the sleeper and sub ballast – under sleepers (ballast thickness varying from 250 mm to 450 mm, from sleeper bottom), between sleepers (crib ballast around 600 mm, between two adjacent sleepers) and on both sides of sleepers (shoulder ballast varying from 300 mm to 500 mm, from both sleeper sides).

Normally, according to Indraratna et al. (2011), the ballast consists of strong, hard, durable, medium to coarse-sized granular and angular particles (from 10 mm to 63 mm) with a large number of voids (pore space). It must provide both a permeable structure to facilitate a fast drainage, and a high load bearing capacity (Indraratna and Ngo 2018, and Ngamkhanong 2020). The ballast is the bottom-most layer of a ballasted railway track superstructure. At the sleeper-ballast interface, it is usually tamped and compacted around the rail-sleeper side up from 300 mm to 500 mm (Peplow et al. 1996, and Li 2019).

As the railway track structure is placed on a “floating” support (a ballast bed) and suffers the influence of dynamic loads during the traffic, the ballast degrades under railway traffic (Lichtberger 2011). It occurs because of not only the ballast breakages (angular corners and sharp edges) and abrasions resulting in permanent ballast plastic deformations, but also the infiltration of fines from the surface (and/or dropped from wagons, e.g., fines of iron ore or coal) and the mud pumping from the subgrade under cyclic loadings, which reduce the ballast strength and block the drainage (Indraratna and Ngo 2018, and Guo et al. 2022). These actions increase track deformation and cause differential track settlements promoting the track geometrical degradation (Selig and Waters 1994). Figure 2.0-5 illustrates examples of different ballast conditions.



Figure 2.0-5. Examples of different ballast conditions: fresh ballast (right), recycled ballast (medium), and fouled ballast (left) (Costa 2016, and Costa et al. 2017).

The railway ballast performs some well-defined functions as follows (Hay 1982, Profillidis 2006, Lichtberger 2011, Indraratna et al. 2011, Ngamkhanong 2020, and Guo et al. 2022):

- Supporting sleeper uniformly.
- Further distributing forces transmitted by sleeper from sleeper/ballast interface to sub ballast and subgrade.
- Attenuating the greatest part of train vibrations.
- Resisting track shifting (transversely and longitudinally).
- Providing a good water permeability to keep the sleeper in a dry condition and to maintain the bearing capacity of the railway track infrastructure.
- Ensuring elasticity and resilience to minimize dynamic forces.

The ballast functions described above are clearly conflicting in some conditions, thus a railway ballast cannot entirely accomplish all of them. For example, Profillidis (2006) and Li (2019) argue that for good bearing characteristics and added railway track stability, the ballast is required to be well-graded and compact which, in turn, difficult an adequate permeability for

drainage. Therefore, a balance among those functions must be achieved so that the ballast can perform as required. Additionally, a well-compacted crushed ballast below the rail side sleepers has a reduced initial pore space, which causes the increase of ballast density and, consequently, its strength, modifying the wave speeds of the ballast and, consequently, its natural frequency (or wavelength) (Tutumluer et al. 2018, Foster et al. 2021, and Melo et al. 2022).

According to Zhai (2020), the performance characteristics of the ballast layer consist of durability, resilience, strength, stiffness, and stability (Guo et al. 2022). On-site measurements of deformations and stresses under repeated loadings have shown that ballast behavior is elastic-plastic conforming to the Drucker-Prager criterion (ORE-D-71 1978) indicating to be the ballast a hardening material. In this case, once yield takes place, the load requires to be continually increased to drive the ballast plastic deformation (Chen, W. F., and Baladi, G. Y. 1985, and Pietruszczak 2010). Indraratna et al. (2011) consider that the ballast bed harden is caused not only by ballast breakages and abrasions but also (and consequently) by the fouling, which means that the ballast layer becomes likewise a cemented concrete with the fouling as binder driving the ballast to lose its resilience. Furthermore, it means that the ballast track geometry is usually irregular leading to a fast degradation (Indraratna et al. 2018).

Both laboratory and field experiments have indicated that on initial loading, the ballast experiences a great permanent deformation (plastic deformation) due the rearrangement of the ballast rocks (stones) to reach a state of equilibrium (Hay 1982, Profillidis 2006, and Indraratna et al. 2011). In subsequent cyclic loadings, the contribution of the plastic deformation to the total deformation is smaller (Indraratna et al. 2011, and Melo et al. 2022). Accordingly, three-axle experiment has revealed that plastic deformation of ballast ' ε_p^N ' at the 'N-th' cyclic loading may be expressed as a function of the plastic deformation at the first cycle by as follows (Profillidis 2006):

$$\varepsilon_p^N = \varepsilon_p^1 * [1 + c * \log(N)] \quad (2.1)$$

where ' ε_p^N ' is the deformation at the 'N-th' cyclic loading, ' ε_p^1 ' is the first cycle deformation, 'c' is a constant depending on some operational, vehicle and track conditions varying from 0.2 to 0.4, and 'N' is the number of cyclic loadings.

Most of the laboratory experiments' results fit with the linear form of Equation 2.1. Nonetheless, a few other experiments have indicated a non-linear behavior for the plastic deformation of ballast (Profillidis 2006, and Indraratna et al. 2011). According to Guo et al. (2022), in earlier studies, the characteristics affecting the performance were investigated with the laboratory or field experiments (e.g., sleeper supporting stiffness measurement), and numerical modellings of the corresponding investigations were also simulated, which indicate mature at both the basic knowledge and methodologies as also pointed out by Melo et al. (2020). However, as mentioned by Melo et al. (2022), there is not a harmony among the test conditions under which the investigations were performed and, hence, among the outcomes. As highlighted by Guo et al. (2022), the mechanism of ballast bed degradation and the associated plastic deformations have not been revealed clearly, and the problem becomes more complicated, due to the increasing train velocities and heavy-haul axle loads.

As there are many factors that influence the ballast bed degradation mechanism, its investigation has become a challenge. Indraratna et al. 2011, for example, consider at least 16 parameters to predict railway ballast degradation, whereas other researchers indicate just one, which necessarily causes different conclusions. In this research, the performance characteristics of ballast is regulated by three hardening material parameters: elastic stiffness, yield force and tangent stiffness. Additionally, it is considered the damping parameter of ballast to meet one of

its functions: attenuation of train vibrations (Costa 2016, Costa et al. 2017, and Melo et al. 2019). Figures 2.0-6 and 2.0-7 illustrate, respectively, the force-displacement curve for considering the elastic-plastic hardening behavior of ballast, and a typical ballast material of heavy-haul ballasted railway track.

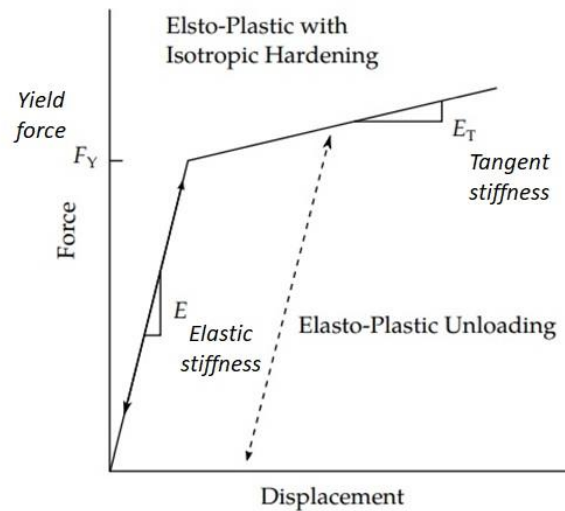


Figure 2.0-6. Force-displacement curve for considering the elastic-plastic hardening behavior of ballast (modified from Indraratna et al. 2011, LS-Dyna 2018, and Melo et al. 2022).



Figure 2.0-7. Typical ballast material of heavy-haul ballasted railway track: track view (left) and sample being quartered to be analyzed in laboratory (right).

According to Selig and Waters (1994), Indraratna et al. (2011), and Li et al. (2016), the ballast deforms a small-scale extent under each cyclic loading, being this deformation chiefly elastic; however, there is a small component of plastic deformity, as above-mentioned. Thus, the ballast bed behaviour is commonly best described in terms of a limiting deformation principle, which is different from statically loaded geotechnical structures where strength is characterized considering the material collapse and not the deformity (Li et al. 2016). That ballast deformity can be due to (1) settlement and particle rearrangement, which is describe by Li et al. (2014) as a phenomenon where the horizontal level of a ballasted railway track component (e.g., railway ballast and/or infrastructure components) loss in height over time when under cyclic loadings. Ballast deformation can also be due to (2) fracture of ballast stones and (3) ballast wear. These three different deformity modes are incorporated by varying degrees to establish the ballast bed deformation. After tamping and (re)compaction of ballast under railway traffic, the ballast particles will be forced into contact, thus the layer becomes increasingly resistant to deformation with further cyclic loadings. Under these conditions, the rate of ballast plastic deformation decreases gradually (Indraratna et al. 2011, and Li et al. 2016). Figure 2.0-8 depicts the influence of ballast stiffness and damping on the magnitude of railway track receptance indicating that the fresh crushed ballast properties mainly affect the first fundamental mode (Li 2016): (1) increasing railway ballast stiffness boosts the fundamental frequency and reduces the magnitude of rail displacement, and (2) boosting in railway ballast damping leads to a reduction in magnitude of track deformation at the essential frequency. The essential frequency is between 50 and 210 Hz, depending on the ballast stiffness.

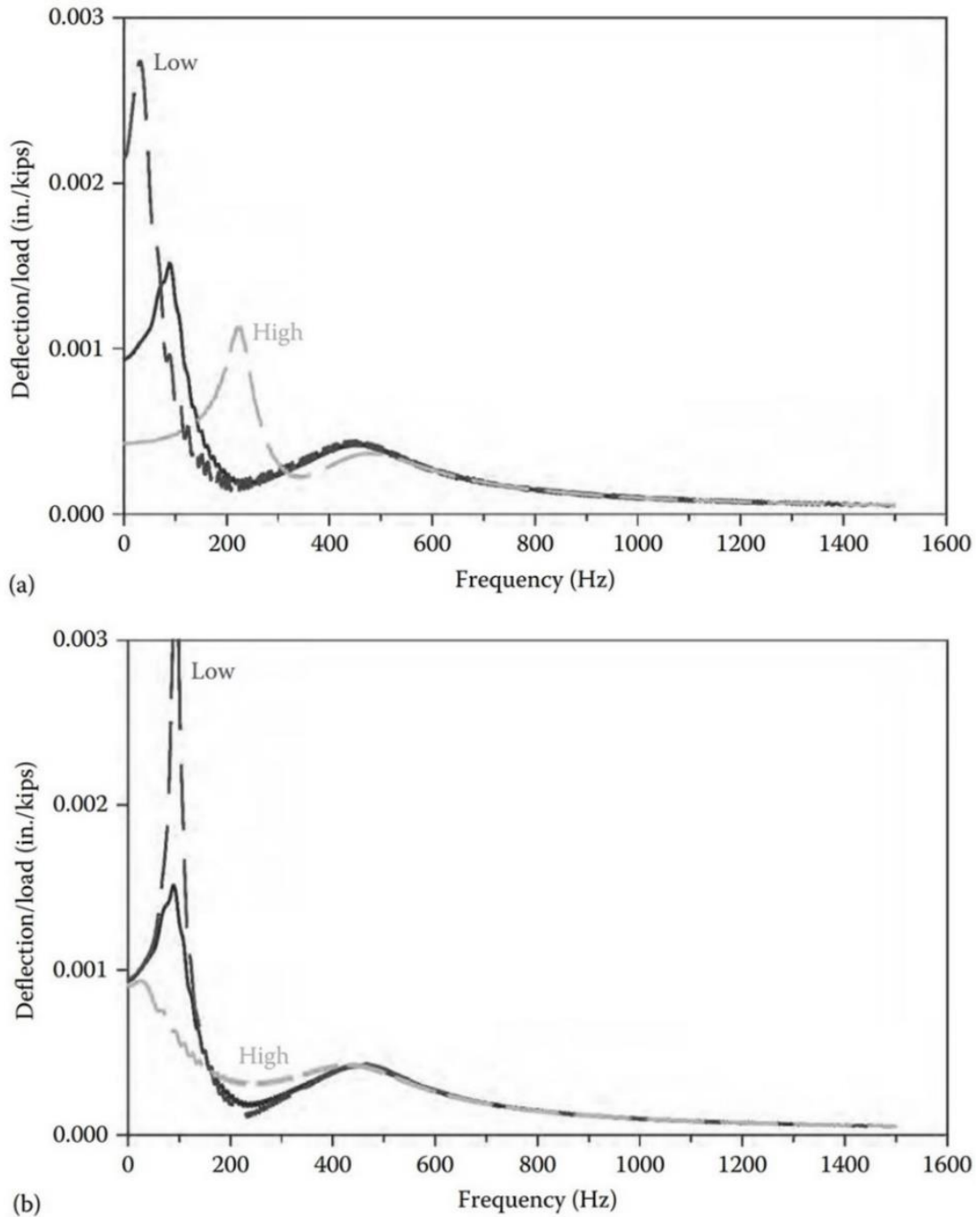


Figure 2.0-8. Effect of fresh crushed ballast elastic stiffness (a) and damping (b) on vertical displacement of a ballasted railway track (modified from Li et al. 2016).

Another issue arising from ballast deformation is that inevitably the ballast settles differently (known as differential settlement) influenced by stiffnesses under, in, and above

itself, which usually lead to form a gap between the sleeper and the ballast, namely, “unsupported sleepers” or “hanging sleepers” track (Tzanakaki 2013, Zhang et al. 2008, Zakeri et al. 2015). It was often found that the sleepers hanging from the rails were very recurrent at a typical railway location (over 50%) (Melo et al. 2023a). In this track condition, some parts of rail remain suspended due to its high flexural stiffness, which causes the formation of the track with unsupported sleepers leading the escalation of dynamic forces on a ballasted railway track (Melo et al. 2023a). Understanding these conditions (plastic deformation behaviour and “unsupported sleepers” occurrences) are important to develop new strategies and methodologies for assessing a ballasted railway track life for maintenance proposes.

2.2.6. Sub ballast

Also called “capping”, it is a select crushed stone or gravel and sand mixture layer between ballast and subgrade (Selig and Waters 1994) being placed as a specific layer with a prevailing 150-mm thickness (Indraratna et al. 2011). As a structural layer of ballasted railway track, the capping reduces stress to the subgrade, like ballast, depending on its resilient modulus and thickness (Li et al. 2016). A typical well-graded capping layer allows a high relative density, and consequently, high resilience module. According to Selig and Waters (1994) and Li et al. (2016), the sub ballast must not deform plastically under cyclic loadings, which requires that the sub ballast be well-drained and have durable angular particles that interlock and resist breakages and abrasions. Figure 2.0-9 illustrates a typical sub ballast material of heavy-haul ballasted railway track.

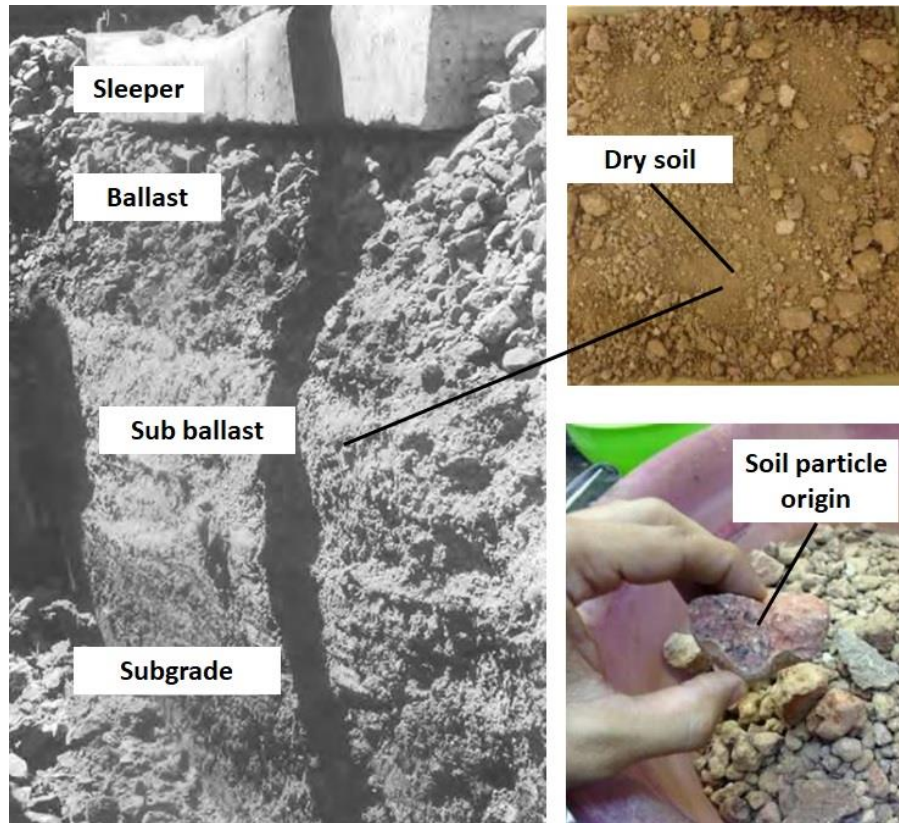


Figure 2.0-9. Typical sub ballast material of heavy-haul ballasted railway track (modified from Li 2016, and Costa 2016).

2.2.8. Subgrade

Also known as formation layer, the subgrade is the platform upon which the track structure is constructed. According to Indraratna et al. (2018), it may be classified into two parts: (1) formation (natural ground), and (2) filling soil (placed soil). Its main function is to provide a stable foundation for the sub-ballast and ballast layers (Selig and Waters 1994). It is also known as the foundation on which all ballasted railway track components above depends for support. It must be stiff and have a bearing capacity qualified to support repeated loadings at the sub ballast/subgrade interface. Even though the formation layer is the most variable, and the weakest of ballasted railway track components (Li et al. 2016), it must provide a stable platform

being able to prevent excessive deformation and consolidation settlement (Selig and Waters 1994, and Indraratna et al. 2018).

2.2.7. Reinforcement of subgrade

The subgrade must have enough bearing capacity and stability, reasonable settlements behavior, and must provide good drainage (Esveld 2001). If the existing formation cannot meet these requirements adequately, the soil can be improved by digging a trench and filling it with a proper compacted soil. This practice is usually called reinforcement of the subgrade.

2.3. Track Geometry of Ballasted Railway Track

Track geometry is an important aspect of railway construction and maintenance (Esveld 2001), particularly for the current challenges of increasing train velocities, axle loads, traffic volume (passenger and freight), and climate changes. It refers to the geometric problems of curve and tangent (straight) design, use, and maintenance (Hay 1982). Track geometry can also be defined simply as 3D geometry of track (Soleimanmeigouni et al. 2018).

A railway track is composed of straight segments with circular and/or transition curves connecting tangents of different directions, and the rails are spaced a uniform gauge distance apart. Maintaining gauge, surface and line are primary track maintenance functions (Hay 1982).

The essential geometry elements are measured in the cross-section of the track as drawn in Figure 2.0-10. According to Esveld (2001), each rail has two degrees of freedom, and these four degrees of freedom are usually replaced by an equivalent system consisting of gauge, vertical levelling (also known as vertical profile or longitudinal level), lateral alignment, twist, and cross-level (also known as cant or superelevation). They represent the track geometry (BS-

EN-13848-1 2019, and Alcocer 2019), which together represent the track geometry of a ballasted railway track.

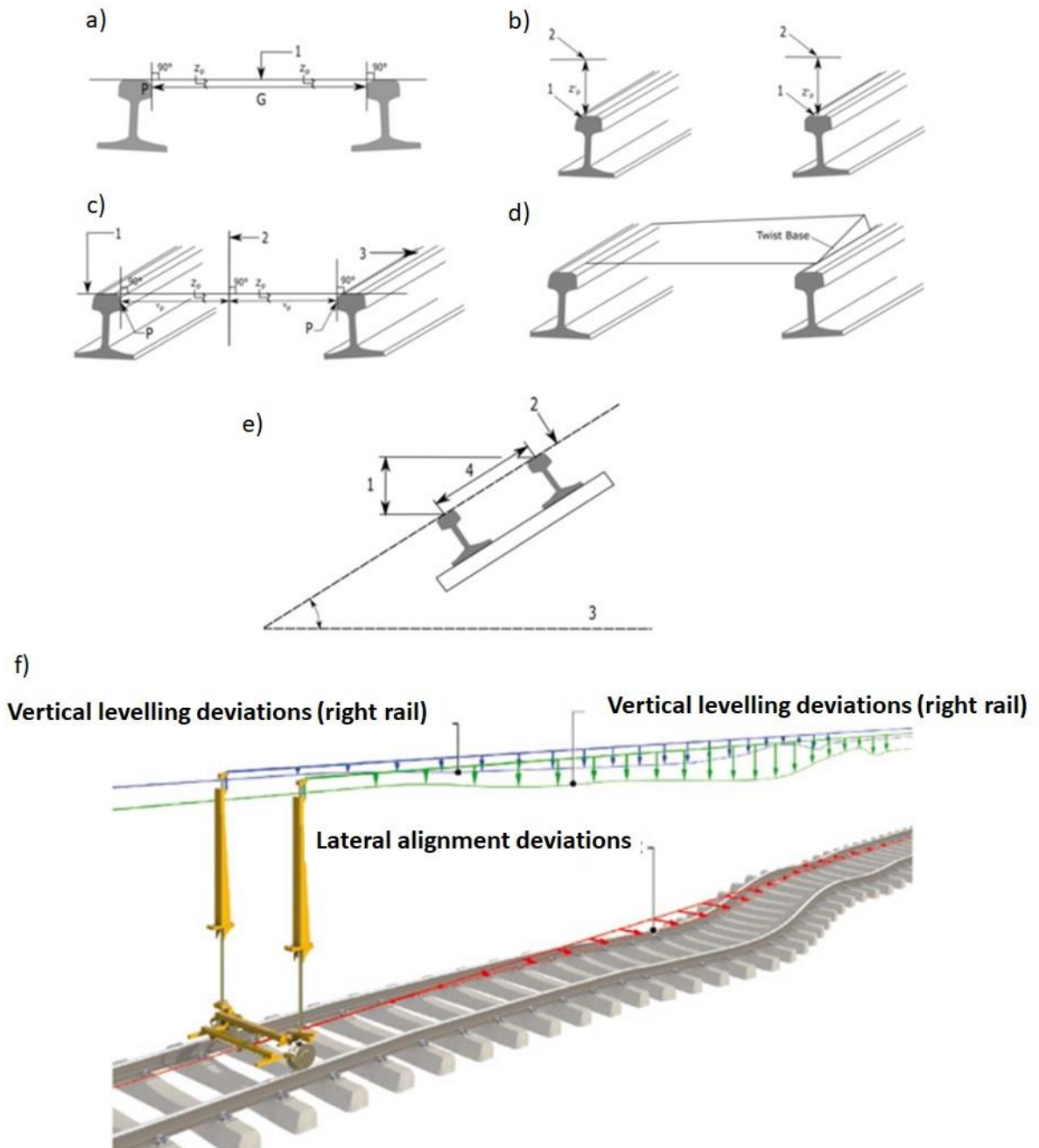


Figure 2.0-4. Essential track geometry elements of a ballasted railway track: (a) gauge, (b) vertical levelling, (c) lateral alignment, (d) twist, and (e) cross-level (modified from EN-13848-1 2019, and Alcocer 2019); (f) track geometrical irregularities.

2.3.1. Track geometric elements

The ballasted railway track, like other types of infrastructure, must be maintained. Aside from the static and dynamic requirements cause by the loads and traffic volume, the track geometry is subject to weather influences. The life cycle of the track components is limited, depending on stress and length of use, which means that these components must be replaced after this period has overdue (Lichtberger 2011). It is important to understand that good track geometrical elements apply to the track in its loaded rather than unloaded position. Three indicators can describe the track geometric quality: (1) extreme values of isolated defects, (2) standard deviation over a defined length, and (3) mean value (EN-13848-5 2008). According to EN-13848-1 (2019), the geometrical elements are described as the followings:

2.3.1.1. Gauge

The gauge is the smallest distance between lines perpendicular to the running surface intersecting each rail head at point 'P' in a range from zero to a fixed distance ' Z_p ' (14 mm), below the running surface '(1)'. The main gauge distances in railways around the world are 1,600 mm (broad or large gauge), 1,435 mm (standard gauge), and 1,000 (narrow gauge). Rails, fastening systems, and sleepers are the track components that play an important rule to keep the gauge within the defined thresholds as well as the characteristics of rolling stock (train vehicles, particularity the traction vehicles).

2.3.1.2. Vertical levelling

The vertical levelling (VL) or vertical profile (or longitudinal level) is the deviation ' Z_p ', of consecutive running table (1) levels on any rail (e.g., left or right rail), expressed as an excursion from the mean vertical position of a reference line '(2)'. It is the most reliable in indicating the

influence of the vertical loads on track quality and is the principal factor (together with the lateral alignment) in determining the intensity of the track maintenance expenses (Profillidis 2006). Any weakness in the railway track superstructure and infrastructure, particularly subgrade, reinforcement of subgrade, sub ballast and ballast will negatively affect the longitudinal level (Hay 1982, and Melo et al. 2022). Mostly ballasted railway tracks present a degree of VL deviation (or initial track irregularities) (Melo et al. 2023b), which must meet the requirements defined by the maintenance standards such as EN-13848-5 (2008).

Inconsistencies in the vertical profile all lead to amplify the dynamic forces exerted by train's wheels on the track, and therefore to vertical dynamic motions of the train (Esveld 2001, and Adeagbo et al. 2021). These forces between wheel and rail, which arise from those motions, are overlapped on top of the static wheel-rail force arising from the total mass of the vehicle. Not only these forces affect vehicle safety, passenger ride quality, and useful life of service of vehicle and of track, but they can also cause progressive degradation of the railway track vertical profile (Dahlberg 2006). This degradation of the VL usually aggravates the uneven support mentioned before, which may lead to even larger dynamic forces and further increasing track geometrical vertical levelling loss (VLL), which is defined by Melo et al. (2022) as a parameter of how much the rail losses its vertical position in the railway tracks physical space under cyclic loadings. According to Soleimanmeigouni et al. (2018), the vertical profile defects represent more than 50% of track geometric irregularities in a ballasted railway track. Figures 2.0-11 and 2.0-12, respectively, illustrate the occurrence of track geometric irregularities, and an example of track geometrical VLL in a ballasted railway track.

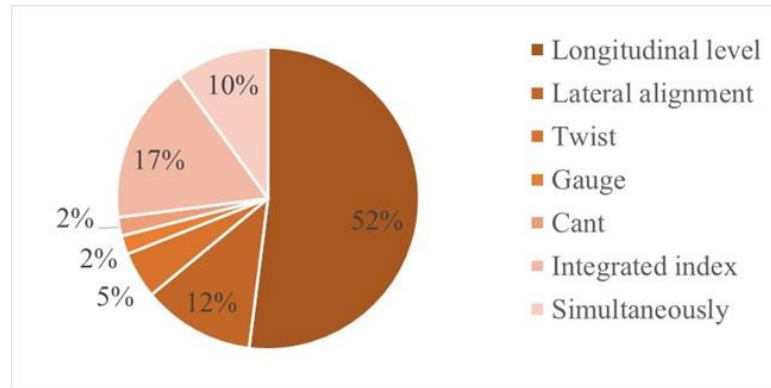


Figure 2.0-5. Occurrences of track geometric irregularities in a ballasted railway track (modified from Soleimanmeigouni et al. 2018).



Figure 2.0-6. Example of track geometrical VLL in a ballasted railway track (Lazorenko 2019).

2.3.1.3. Lateral alignment

The lateral alignment is the deviation ' Y_p ' in y-direction of consecutive positions of point P on any rail, expressed as an excursion from the mean horizontal position from a reference line '(2)' and the center line of a railway track. It depends on the vertical levelling effects and on the

characteristics and particularities of rolling stock (particularly the traction vehicles). As pointed out by Hay (1982), the effects of poor alignment are rough riding, excessive and irregular rail wear, and a serious contribution to poor vertical profile.

2.3.1.4. Cross-level

The cross-level or cant (or superelevation) is the difference in height '(1)' of adjacent running tables computed from the angle between the running surface '(2)' and a horizontal reference plane '(3)'. It is expressed as the height of the vertical leg of the right-angled triangle having hypotenuse '(4)' that relates to the nominal track gauge plus the half width of the rail head. In general, along straight segments the cross-level is set zero cant, whereas on transition and circular curve it is determined to, respectively, vary from zero (just before the end of the straight segment) to a maximum adequate value (at the beginning of circular curve segment), and maintain that last value (keep it constant) along of all circular curve segment. The maximum values (or maximum superelevation) depend on the radii of curve segment and the train velocity. As the vertical profile element, the cross-level relies on the railway track superstructure and infrastructure, particularly ballast, which under cyclic loadings can lose its capacity of supporting the sleepers consistently, and consequently increase that track geometric irregularity.

2.3.1.5. Twist

The twist is the algebraic difference between two cross-levels taken at a defined distance apart. The risk of derailment is prevented when the real value of twist is smaller than its critical value causing derailment, which depends on train velocity and to a lesser degree on the type of track equipment and of the rolling stock. It can therefore be concluded that the track twist and lateral

alignment are not independent. However, they are often examined separately because track twists are one of the most frequent causes of derailment, particularly for train velocity higher than 140 km/h (Esveld 2001, and Profillidis 2006). Along straight and circular segments (where superelevation is constant), four points of the track lying on two transverse sections (e.g., on two sleepers, as shown in Figure 2.0-13) must lie in the same plane. Thus, the track twist is defined as the deviation of one point from the plane defined by the other three. If ‘i’ and ‘i + 1’ are two successive transverse sections of the track, spaced ‘ Δl ’ apart, the track twist is defined as the variation of the transverse defect per unit length as follows (Profillidis 2006):

$$\text{Track twist (mm)} = \frac{TD_{i+1} - TD_i}{\Delta l} \quad (2.2)$$

where ‘ TD_{i+1} ’ is the transverse defect 1, ‘ TD_i ’ is the transverse defect 2 (adjacent to the defect 1), and ‘ Δl ’ is the distance between the two transverse defects.

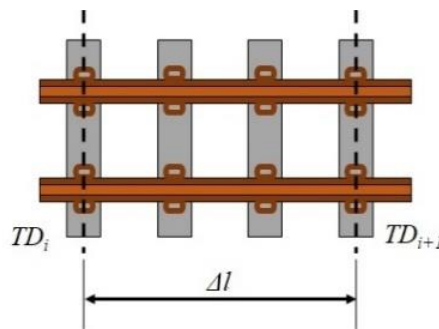


Figure 2.0-7. Track twist: the deviation of one point from the plane define by the other three (modified from Profillidis 2006).

2.3.2. Track geometric quality assessment

Competent maintenance personnel detected track defects until some decades ago either visually or by simple instruments (Profillidis 2006, and Lichtberger, 2011). Nonetheless, in recent years,

modern railways are using the technology of track recording car, which travels the track at specified periods depending on the route. These vehicles are provided with recording equipment, which measures the values of the defects of track geometric elements in accordance with a specific bases of measurements. Vertical levelling and lateral alignment elements are typically measured with inertial measurements system into wavelengths determined by EN-13848-3 (2009).

The distribution of the diverse types of track geometric irregularities is of stochastic nature and can be approximated with the aid of spectral analysis (Esveld 2001, and Profillidis 2006). Thus, for each class of track geometric irregularities, the following can be calculated: (1) their frequency of occurrence, (2) the wavelength to which they correspond, (3) their relation to train velocity, and (4) their position along the track. Figure 2.0-14 shows an example of track recording car (in details, respectively, the track geometric irregularities diagram, and the vertical levelling track geometric defects recording by a heavy-haul railway recording vehicle).

In usual railway systems, there are numerous approaches for assessing the track geometric quality (TGQ). According to Alcocer (2019), those approaches can be divided in three major groups: (1) statistical assessments, (2) vehicle response analysis, and (3) frequency analysis.

The statistical methodologies assessments of track irregularities usually apply elementary standard deviations or weighted of the given track geometric elements to generate quality indices. The outcomes are opposed to accepted values to determine safety related thresholds or intervention limits (Esveld 2001). Another statistical approach is the explicit contrast of maximum values of a specific track irregularity against standard values such as those indicated in EN-13848-5 (2008).

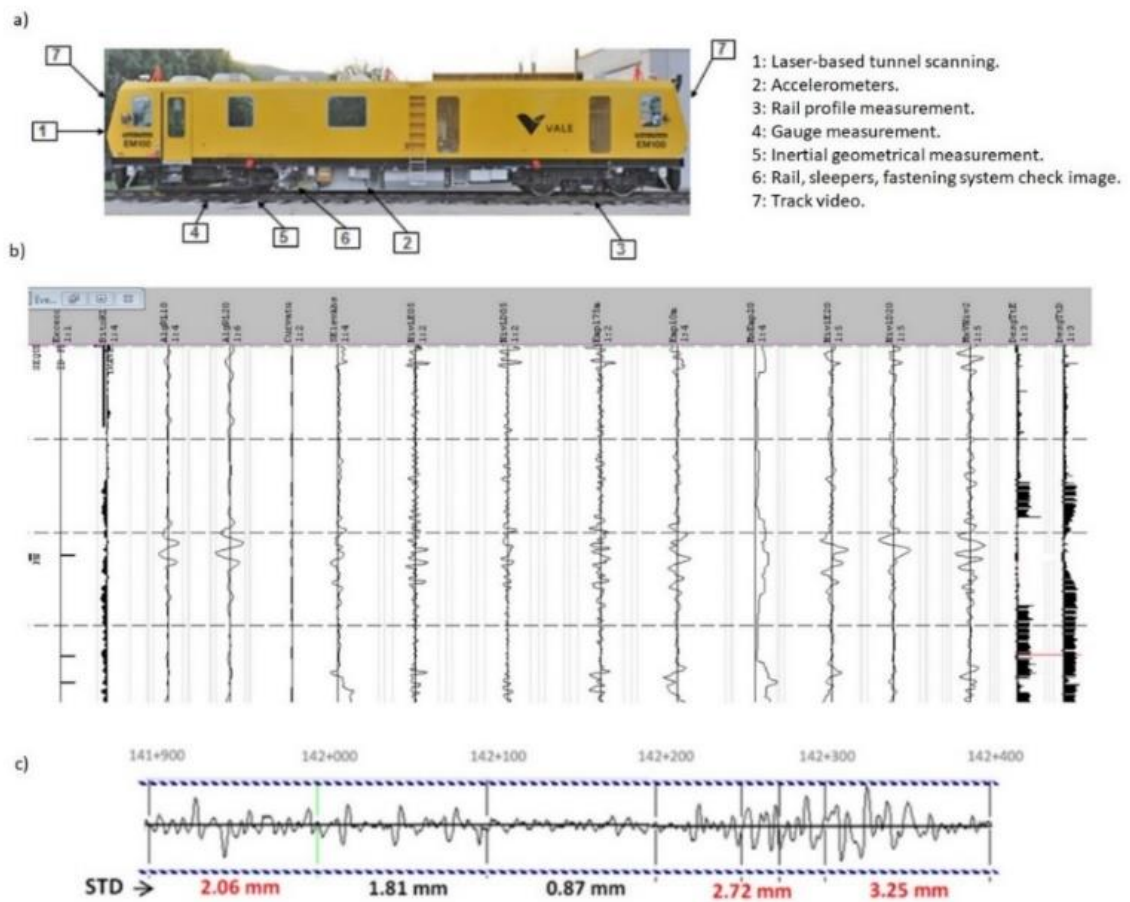


Figure 2.0-8. Example of track recording car, and in details, (a) track geometric irregularities diagram, and (b) the vertical levelling track geometric defects recording by a heavy-haul railway recording vehicle (modified from Silva et al. 2016).

Standard Deviation Index (SD Index, or simply SD) is one of statistical methodologies applied worldwide. It considers seven standard deviations related to measured values on a specified track section or segment as illustrated in Figure 2.0-15. According to Berawi (2013), it is recommended that the SD as above-described be calculated for track sections of 200 m for the vertical levelling and alignment, and for 100-m section for gauge. The SD Index is calculated as follows (Alcocer 2019):

$$SD_i = \sqrt{\frac{1}{n} \sum_{j=1}^n (x_{ij}^2 - \bar{x}_i^2)}, \text{ with } \bar{x} = \sum_{j=1}^n \frac{x_{ij}}{n} \quad (2.3)$$

where ‘ SD_i ’ is the standard deviation of a specific track geometric irregularity, x_{ij} is the measurement value in *mm* at the j -th point of a railway track section, and ‘ n ’ is the number of samples in the track section.

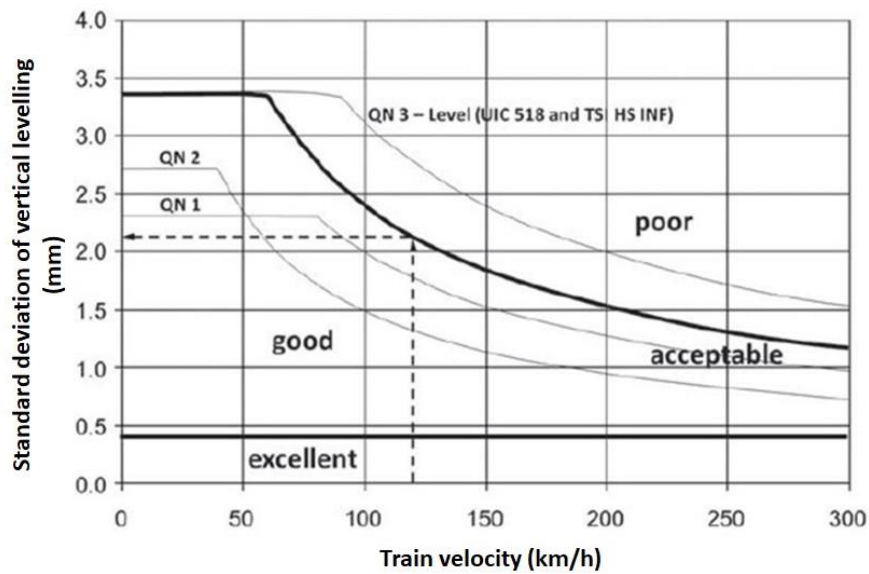


Figure 2.0-9. Example of SD intervention of vertical levelling to maintain a constant riding comfort at different train velocities (UIC 2008, Osman 2020).

Multibody Simulation (MBS) is a vehicle response method developed to evaluate TGQ, which includes track/vehicles interaction responses against maximum values defined by, for example, per BS-EN-14363 (2016). The parameters are captured through performance simulation of accepted MBS vehicles (Iwnicki 2006). According to BS-EN-13848-6 (2014), they are the vertical wheel forces (maximum and minimum), the sum of lateral forces per wheelset, the quotient of lateral and vertical forces per wheel, and the maximum both vertical and lateral vehicle acceleration. In turn, the track geometric elements are vertical levelling,

lateral alignment, and cant. They are evaluated considering the overlap of vertical and lateral track geometric irregularities (Gadhavé and Vyas 2022). Similarly, the track geometric elements values can be applied to statistically calculate TQI (track quality indices) values for a specified railway track segment (BS-EN-14363 2016).

Signals are usually captured by temporal or spatial sampling of continuous signals (Alcocer 2019). However, an evaluation of railway track geometric elements is not simply done with signals in the spatial domain, particularly because it is arduous to determine the shape of track geometric elements defects and their wavelengths (or frequencies) contents. Power spectral density (PSD) function is one of frequency analysis methods to assess track irregularities showing them by means of wavelength (or frequency) content (Zhang et al. 2010, and Gadhavé and Vyas 2022). The values are usually provided in a power spectrum graph (PSG), which is a continuous curve with the ordinate denoting spectral density and the abscissa as spatial frequency (Gadhavé and Vyas 2022). According to Berawi (2013), PSD can support the characterization of geometric elements of a railway track segment as indicated in standard EN 13848-6 (2014), in terms of wavelength and amplitude showing regular maximum values of repeated track geometric defects. ERRI-B176 (1993) standard (also identified as the German PSD) is one of the most used standards in research, used for dynamic simulation of railway vehicles.

2.4. Railway Vehicle-Track Dynamic Interactions

A heavy-haul train subsystem is composed by several locomotives and a series of railway vehicles, longitudinally interconnected by couplers. In turn, a heavy-haul railway vehicle consists of a vehicle car body, two bogie frames and four wheelsets laterally and vertically interconnected by secondary and primary suspensions (Spiryagin et al. 2014). According to

Iwnicki (2006), the principal difference between a railway vehicle and other types of wheeled transport is the guidance provided by the track. The surface of the rails not only supports the wheels, but also guides them in a lateral direction. The rails change the rolling direction of wheels and thus determine the travelling direction of the railway vehicle.

A railway vehicle is formed of many components and for vehicle-track dynamic interactions, it is interesting to understand the parameters of the key components. It can be divided in two main sets: (1) body components, and (2) suspension components. Basically, it consists of a body supported by secondary suspension on bogies in which the wheelsets are mounted and damped by means of primary suspension (Esveld 2001). Figure 2.0-16 illustrates the key railway vehicle components and their respective position on a typical heavy-haul wagon (vehicle).



Figure 2.0-10. Key railway vehicle components and their respective position on a heavy-haul wagon framework (modified from Santos 2015).

The key suspension components (1st and 2nd suspensions) are discrete physical springs and dampers whose forces are related to the train speeds and displacements at the suspension components. They play important roles in decreasing car body and bogie frame accelerations as well as dynamic wheel-rail contact forces influencing noticeably the railway track geometrical degradation, expressly the vertical levelling. They also permit for appropriate curve negotiation, but a too soft suspension causes problems with vehicle gauging (Polach et al. 2006).

2.5. Railway Operational Conditions

The requirements for behaviour strength and quality of the railway track depend to a large amount on the operational conditions: (1) axle load, (2) traffic volume, and (3) train velocity (Esveld 2001, and Profillids 2006). The axle load or vertical load per axle, to which the dynamic accretion is added, is assumed to regulate the needed strength of the railway track. It varies from 5 to 40 tons per axle for, respectively, unloaded (no goods in the wagon, just the tare) and loaded heavy-haul wagons. In turn, the traffic volume or the number of axle loads is a measure of when an intervention (maintenance or renewal) is required. In heavy-haul railways it is usually over 50 MGT (million gross tons) per year or, for 25-tons axle load vehicle, around 2 million load cycles (Profillids 2006, Lichtberger 2011, and Tzanakakis 2013). Figure 2.0-17 illustrates a typical iron ore train composition of a heavy-haul railway with loaded wagons.

The dynamic load component by moving railway vehicles, which depends on train velocity and horizontal and vertical railway track geometric elements, also plays a fundamental role on track geometrical degradation as it superimposes on the static load, as pointed out by Li (2019). Some studies have clearly indicated the influence of the railway vehicle loading on vertical levelling of track geometry. According to Iwnick et al. (2000), railway tracks that

transport fast and heavy-haul trains necessity more periodic maintenance. It is estimated that in heavy-haul railways the traffic volume cause more than 90% of track geometrical degradation overall (Stichel 1999).



Figure 2.0-11. Typical iron ore train composition of a heavy-haul railway with unloaded wagons (8 distributed locomotives and 333 wagons).

After enhancing the influence of million load cycles (traffic volume) by the axle load and train velocity, it is possible to note that these three operational parameters contribute to a large extension to accelerate the rate at which a ballasted track of heavy-haul railways degrades their track geometry. Furthermore, as train velocities and wheel loads have increased along with the rationalization of lines, demands on the railway track structure have increased substantially. According to Li et al. (2016), the increase in velocity for freight traffics was bolstered by higher traction power, heavier traction vehicles (e.g., locomotives) with higher adhesion leading to larger railway track forces, and heavier railway cargo vehicles.

2.6. Forces Acting on a Ballasted Railway Track

As previously mentioned, the forces acting on a ballasted railway track has changed substantially; increasing train velocities, axle loads, traffic volumes and even weather conditions challenge the railway track daily. It is expected that the railway track structure counters these effects. According to Esveld (2001) and Lichtberger (2011), the forces that acting on a ballasted railway track can be categorised into 3 main groups: (1) vertical forces, (2) lateral forces, and (3) longitudinal forces.

Vertical forces are the direct forces consequence of loads transmitted through the wheels depending on the vehicle axle load, the train velocity, and the railway track geometric elements (e.g., vertical levelling). In turn, lateral forces are the forces acting perpendicular to the railway track due to wheel-rail contact point stressing the rails horizontally and at a right angle to the railway track axis depending on the vehicle technical parameters (e.g., bogie design, wheelbase, and elastic and damping constants), the track segments (e.g., radii of curve segment), the steering effects (markedly large in curve segments, but it can occur on straight tracks), the axle loads, the train velocity, the wind effects and the railway track geometric conditions (e.g., cant).

The 3rd category of forces that act on a railway track is the longitudinal forces. They are the forces parallel to the railway track due to (i) the change of length in the rails caused by temperature, (ii) the acceleration/breaking of railway vehicle composition, and (iii) the rail creep.

Depending on the railway track components, they must absorb and distribute different forces accordingly (Hansmann et al. 2021). If the forces exceed a defined magnitude or act on the sub-system for a lengthened period, individual components start to wear, settle, or fail because of fatigue process resulting not only in a failure of components due to deterioration, but also a complete collapsing of railway track sub-system due to track geometrical degradation.

Figures 2.0-18 and 2.0-19 illustrate, respectively, the main groups of the forces that act on a ballasted railway track and its directions and the forces acting at the wheel-rail contact point.

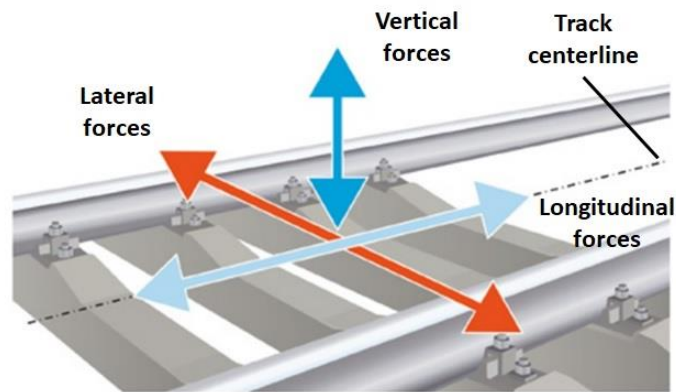


Figure 2.0-12. Main groups of forces that act on a ballasted railway track and its directions (modified from Hansmann et al. 2021).

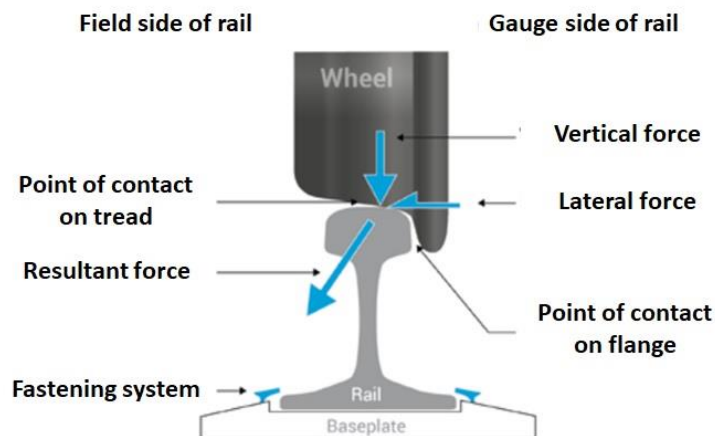


Figure 2.0-13. Forces acting at the wheel-rail contact point (modified from Hansmann et al. 2021).

The loads are irregularly distributed over the two rails, and they are often difficult to evaluate quantitatively (Esveld 2001). Depending on the nature of the loads, they can be divided

into 3 groups (Martyn 2005, Kaewunruen and Remennikov 2007, and Tzanakakis 2013): (1) static loads, (2) quasi-static loads, and (3) dynamic loads.

The static loads are caused by the mean weight of railway wagons (freight), unaffected over an extended period, and identical to the wheel-rail contact force if the treaded wheel and rail surface are perfect. In turn, the quasi-static (or dynamic ride) loads are applied to design method changing marginally its magnitude over a prolonged period. The dynamic ride loads are the sum of the static load associated with the influence of train velocity, together with railway track supports and geometric elements, and vehicle bogies masses in reaction to track irregularities. Also, they are classified as low frequency forces in the range between 0.5 and 30 Hz, and typically they are between 1.4 and 1.6 higher than the static wheel loads.

On the other hand, the dynamic (or dynamic wheel-rail) loads are, in contrast to static and quasi-static loads, time dependent as its magnitude changes fast within the brief period of time depending on the nature of anomalies. They are caused by significant railway track geometric irregularities and irregular track stiffness (e.g. unsupported sleeper's occurrences, on which ballast voids and pockets underneath the sleeper can occur due to unequal ballast settlements that may cause a gap between the ballast and the sleeper) due to variable characteristics and settlements of ballasted bed and formation, discontinuities at welds and joints, corrugations, and vehicle defects (e.g., wheel-flats).

2.7. Ballasted Railway Vehicle-Track Modelling

An accurate knowledge of the mechanical behaviour of ballasted railway vehicle-track (force, displacement, etc.) is fundamental for sensible design and investigation of the several components of the system, which should satisfy requirements for both economy and safety (Profillidis 2006). Modelling of a railway system can be drawn back at least the early 1970's

and since that time, researchers and engineers have used a combination of empirical, analytical, and numerical FE (Finite Element) methods, existing a variety of them that can be adjusted to the nature of the problem under investigation (Blair and Chan 2006). Each method has specific advantages and drawbacks; thus, they can be employed to different components of the railway vehicle-track system due to their appropriateness and effectiveness. The analytical method is much faster at calculating solution in comparison to the FE method, however the frequency range is more limited and cannot calculate properly a permanent deformation.

Modern methods use finite element analysis, which permits to consider the real geometry and the force-displacement relationship not only statically but also dynamically. Moreover, these analyses (FE) can consider the effect of time, train velocity, vibrations, railway traffic, axle load, vehicles properties (e.g., railway vehicle 1st suspension elastic stiffness), and plastic deformation of track components (e.g., railway ballast tangent stiffness) (Melo et al. 2022). Furthermore, as the vehicle-track system and its components have several types of non-linearity (contacting surfaces, material properties, and geometry), they are exposed to high dynamic forces and displacements that result in a frequency range of from around 2 Hz up to 2,000 Hz (Popp et al. 1999). As a railway vehicle-track system is large and it contains complex components and interfaces, it should properly interact within a highly dynamic operational environment. As pointed out by Blair and Chan (2006), this generates a considerable number of degrees of freedom (maximum number of independent values) being fundamental mathematically to both implement models of part of the system and to make certain hypothesis to govern the consume of computer time process.

The Finite Element Method (FEM), as a discretisation method for investigating issues in mechanical and structural performances (Turner et al. 1956), has demonstrated to be an adequate and applied method during the last three decades (Mottram 1996, and Ngamkhanong

2020). The FEM is underpinned by the decomposition of the domain into a finite number of elements for which an approximate methodical result is constructed by applying differential equations and boundary conditions and assuming approximate functions within each element, which are defined in terms of the values of the field variables at distinct points (assigned as nodes), generally placed along the element boundaries, and connecting adjacent elements (Madenci and Guven 2015).

Distinct types of finite element, including truss, beam, shell, plate, and solid element, which enables diverse types of structures in both two and three dimensions, have been used for diverse structural problems (Profillids 2006, Blair and Chan 2006, Madenci and Guven 2015, Rao 2016, and Ngamkhanong 2020). According to Madenci and Guven (2015) and Rao (2017), this method is composed of various steps, starting from discretising the domain (the structure) of study into small elements and connected each other by their shared nodes. For each element, a local stiffness matrix is first worked, which in sequence is assembled to form a global stiffness matrix. To solve the problem – the nodal forces and displacements, load and boundary conditions are applied.

2.7.1. Ballasted railway track models

For modelling a dynamic wheel-rail interaction in FEM, the level of details (sub-domains or elements) necessary for railway track models is proposed by the frequency range of interest (Torstensson 2012, and Li 2019), and each sub-domain can be modelled differently depending on the purposes of simulations (Tzanakakis 2013, and Ngamkhanong 2020). For a stratified track structure on top of a subgrade which is less rigid than the ballast and sub ballast, a railway track resonance may emerge in the frequencies between 20 and 40 Hz, which indicates that the mass (inertia) of the subgrade should be considered for capture that resonance (Oscarsson

2001). In turn, where part of the railway track superstructure (rails, fastening systems, and sleepers) is vibrating on the subgrade support (the ballast, the sub ballast, and the subgrade), the rails, the fastening systems, and the sleepers are vibrating in phase on the ballast (the support stiffness) in the frequencies between 50 and 300 Hz. On the other hand, in the frequency range 200-600 Hz, there is a rail on fastening system (rail pad) vibration where the rails and sleepers are vibrating out of phase (Oscarsson 2001, and Anderson 2003).

Considering that the ballasted railway tracks are usually comprised of rails, fastening systems, sleepers, ballast, sub ballast, reinforcement of subgrade, and subgrade, each of their components (elements) can be modelled differently accordingly to the objective of the simulations. The rails are linear components of an infinite railway track length (Esveld 2001, and Tzanakakis 2013), which allows to model them as either a beam or a solid element depending on the size and objective of structure investigation (Ngamkhanong 2020). The rails have high flexible stiffness in vertical and lateral directions and compression stiffness in the longitudinal direction. It is important to observe that a beam element is more efficient computationally (lower computer time process) than solid element for predicting the overall behaviour with large railway track modelling, such as vehicle-track interaction and track geometrical degradation, particularly due to beam elements consider axial and shear forces and bending moments (Ngamkhanong 2020). Because of higher flexural stiffness, under railway vehicle loads, the rail vertical displacements and their reactions on the adjacent sleepers on a ballasted railway track model, are aggravated (Melo et al. 2022).

In turn, the sleepers may be modelled as either a beam, a rigid or solid element (Tzanakakis 2013). Xu and Lu (2021) investigated the influence of the sleeper FE types on dynamic behaviours of ballasted railway tracks finding that the influence of element types of modelling sleepers on dynamics of sleepers is larger than that on rails; however, at low- to mid-

frequency range (up to 300 Hz), the differences of the time-domain responses applying models with diverse sleeper elements are usually not that large from technical specification as a typical railway track geometric irregularity excitations has not achieved those high frequencies. They consider that a beam element due its higher computational efficiency and approachable results is an appropriate option. Additionally, they highlight that modelling the sleepers as a rigid body is not recommended as the sleepers resonates due to their distributed mass and stiffness for the case of high frequency excitations (e.g., dipped joint) (Dukkipati et al. 1999). Figure 2.0-20 depicts the comparison of wheel-rail vertical forces using different sleeper elements on time-domain responses, and PSD. Furthermore, Kaewunruen et al. (2018) recommends that the rails and the sleepers should be modelled as solid elements when a single or a few sleepers are studied to simulate dynamic vehicle-track interaction along a short distance.

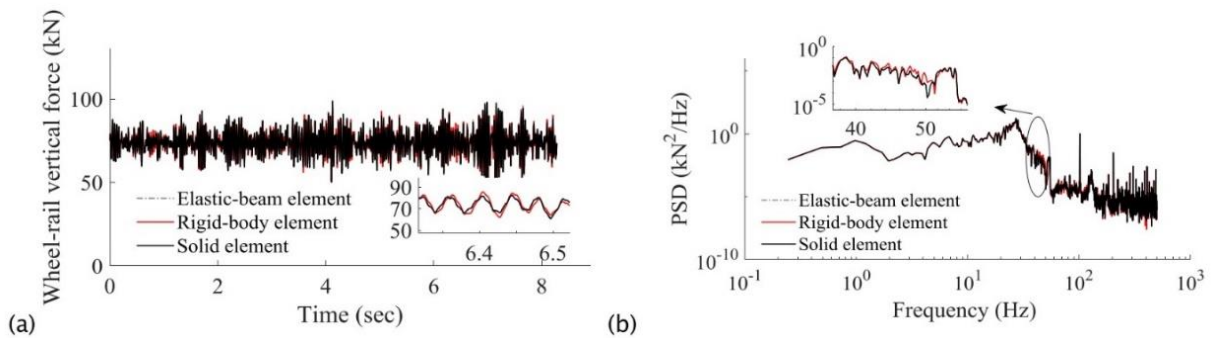


Figure 2.0-14. Comparison on wheel-rail vertical forces using different sleeper elements: (a) time-domain responses, and (b) PSD (modified from Xu and Lu 2021).

The fastening system (rail) usually applied on concrete sleepers' compounds of a resilient spring fastener, undertaking typically in parallel with a much stiffer rail pad (Martyn 2005). Although the load/deflection performance of the fastening system is non-linear (Knothe and Grassie 1993), some linearization of the load/deflection performance can be considered

(Tzanakakis 2013). For vertical vibration, a rail pad is modelled as a spring and damper (viscous dashpot) in parallel; however, depending on frequency-range of study (normally under low and middle frequencies), the damping effect of the fastening system has a minor impact if compared to the damping of the railway track. In addition, the hanging sleepers (unsupported sleepers) would rather pull the fastening systems in tension where damping exhibits little effects. On this ground, it can be assumed that the damper property could be negligible since it would rather offer a worse-case scenario. Rail pads are primarily loaded in compression, permanently by both the fastener (e.g., a clip) and the railway traffic. The inclusion of rail pads is successful in reducing this force as it scales down the effective railway track mass acting on the sleepers and the ballast. The stiffness of each element (component) defines how much the rail is permitted to move within the rail support (seat) influencing the railway track dynamic performance, and consequently the track geometrical degradation (Romero et al. 2010, and Oregui et al. 2017).

Regarding the ballast and the infrastructure components (sub ballast, reinforcement of subgrade, and subgrade), mostly FEM models of ballasted railway track models them as continuum solid (homogeneous) material by discretizing the multilayers into exceedingly small elements (Nguyen et al. 2003, Sasaoka and Davis, 2005). They are usually modelled as a load distributing material and its continuum layer is based on material models that represent its performance (Gallego et al. 2011, and Tzanakakis 2013).

Other investigations, to properly model a railway track taking into consideration a global track behaviour, model railway ballast components as discrete connected elements (springs and dampers) (Ricci et al. 2005, and Kuo and Huang 2009); discrete springs and dampers elements can be used to simulate the interaction between ballast and sleepers under cyclic loadings. Kuo and Huang (2009) studied the influence of different ballast elements (solid elements: elastic continuous material, and discrete elements: springs and dampers) on rail

deflection under different train velocities in FEM. They conclude that the ballast movement in the discrete model is stable for different train velocities. Also, they indicate that differences of maximum deflections between the two models on train velocity over 200-km/h is more serious than that under 100-km/h. Therefore, in case of train speeds below 200 km/h, modelling the ballast of a railway ballasted track as discrete or distributed linear springs and viscous dampers in the vertical direction is acceptable technically to investigate the global track behaviour and justified in terms of reducing the computer time process in FE analysis. Spring elements can also be applied to simulate ballast defects, such as unsupported sleepers, and pockets and voids underneath sleeper, setting it as a compressive displacement, which the discrete element sustains before beginning the force-displacement relation given by a load curve (Zhan et al. 2008, LS-Dyna 2014, and LS-Dyna 2019). Subgrade material is similar to ballast and sub ballast material in its general properties, particularly the load distribution as it affects the mass and the stiffness and damping properties, therefore modelling is considered complicated (Selig and Waters 1994, Tzanakakis 2013, and Li et al 2016). Figure 2.0-21 shows the comparison on ballast deflection using solid and discrete ballast FE. It is possible to observe that the railway ballast motion in the spring/damper (discrete) model suggests a minimum difference for train velocities below 200-km/h train velocity.

Railway ballast and infrastructure components are modelled using linear elastic material models as it requires less computational effort compared to non-linear elastic material models (Alabbasi and Hussein 2021). However, the railway ballast material particularly deflects in a highly non-linear behaviour under cyclic loadings due to pockets beneath the sleepers and voids in the ballast itself (Indraratna et al. 2011, and Sayeed and Shahin 2022). Recent investigations have indicated the importance of modelling a railway ballast component as a non-linear material to capture that behaviour (Indraratna et al. 2011, Gallego et al. 2013, Kalliainen et al. 2016,

Paixao et al. 2016, Costa 2016, Costa et al. 2017, and Melo et al. 2022). According to Alabbasi and Hussein (2021), there are two methods to perform a railway ballast using its non-linearity in FE analysis: (1) the Moher-Coulomb plastic method (commonly applied), and (2) the hardening soil method. Indraratna et al. (2011) recommend applying the non-linearity hardness in modelling railway ballast bed using FEM underpinned by the realistic results captured from large scale triaxial experiments.

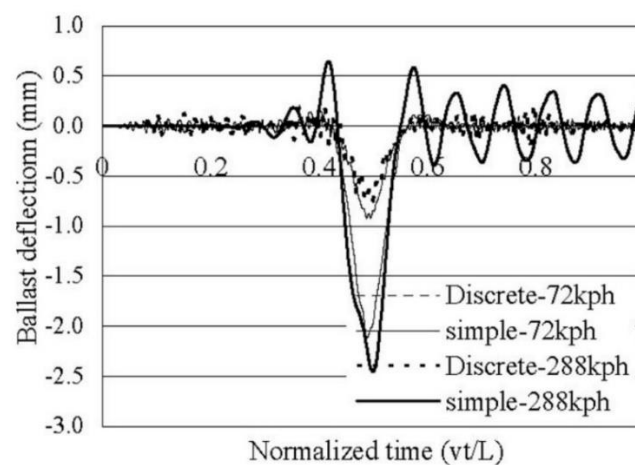


Figure 2.0-15. Comparison on ballast deflection using solid and discrete ballast FE (modified from Kuo and Huang 2009).

The size and the projections (dimensions) of the track model depends on the objective of the FE analysis (Ngamkhanong 2020). Ballasted railway tracks have been modelled in FEM as two dimension (2D), three dimension (3D), and 2.5 dimension (2.5D) (Esveld 2001, Profillids 2006, Ngamkhanong 2020, and Alabbasi and Hussein 2021). Few researchers have studied a ballasted railway track applying 2D FEM models (Alabbasi and Hussein 2021); despite of requiring lower computer time process compared to 2.5D and 3D, it understates the real characteristics of a global ballasted railway track not only because of simplified

assumptions (e.g., plain strain condition, and load application) but also (and mainly) due to not consider both longitudinal load (moving load) distribution and track geometrical irregularities (Indraratna et al. 2011, Jiang and Nimbalkar 2019, and Lassoued and Guettiche 2010). Mostly 2D FEM track models focus on geotechnical aspects of subgrade component.

On the other hand, 3D FEM ballasted railway track models have been applied worldwide, particularly because it permits to study the actual physical railway ballasted track condition in full-scale (Esveld 2001, and Profillids 2006). Numerous investigations have developed 3D track models to consider train-track-soil interaction. Powrie et al. 2007, Sayeed and Shahin 2016, and Varandas et al. 2016 modelled the ballasted railway track using solid elements to represent the ballast and the layers of infrastructure. Differently from those studies, Chen et al. (2021) modelled the ballast of superstructure using discrete elements (springs and dampers). In turn, additionally to Chen et al. (2021), Li et al. (2020) and Melo et al. (2022) suggested to model the subgrade using springs instead of solid elements aiming to reduce the simulation computational time to simulate the effect of cyclic loadings on track geometrical degradation. Alternatively, other studies proposed to model the railway track as 2.5D considering the track geometry of the model constant under moving load to also reduce the computer time process compared to the 3D model (Costa et al. 2012, and Yang and Hung 2001).

In fact, the FEM is a powerful tool in modelling the full railway ballasted track dynamic behaviour and studying the track performance overall under many cyclic loadings allowing to assess the macroscopic behaviour of track components with response to static and dynamic loading. However, it is important to observe that the railway ballast and the track infrastructure components are granular and heterogeneous materials (Selig and Waters 1994, Esveld 2001, Profillids 2006, Indraratna et al. 2011, Ngamkhanong 2020, and Alabbasi and Hussein 2021), and that the FEM can only establish the force-displacement or stress-strain distribution. Also,

it is not capable to perform a detail into particle displacement, breakage, shape, size distribution and fouling, and its granular performance; thus, the FEM cannot directly evaluate some parameters that affect the strength of railway ballast. Furthermore, mostly FEM ballasted railway track models applies the same stiffness parameters for static and dynamic situations in their models (Ganesh and Sujatha 2010). Figure 2.0-30 illustrates different dimensional FEM models.

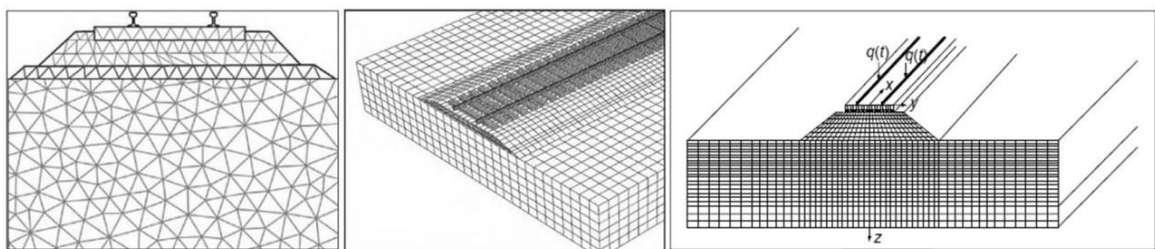


Figure 2.0-16. Different dimensional FEM models (Alabbasi and Hussein 2021).

To study in detail (not the track as a whole) the particle behaviours that can influence the ballast bed and/or the layers of infrastructure, another method should be applied, such as Discrete Element Method (DEM). The DEM is also a powerful numerical method applied to solve mathematical problems related to discrete characteristic material likewise granular material (Huang and Tutumluer 2011). Each ballast particle, for example, has its own properties of velocity, acceleration, displacement, and contact forces. As this method calculates all single contact of the complex realistic shape of particles, it results in higher computer time process and memory space needed, which limits in a single span the modelling of a ballasted railway track (Alabbasi and Hussein 2021). Therefore, the DEM should be used if (only if) the focus is on ballast particle interactions (e.g., ballast breakage) and deterioration (fouled ballast), whereas the other ballasted railway track components should be modelled and investigated

using FEM (Ngamkhanong 2020). Figure 2.0-31 shows an example of DEM applied to investigate different scenarios of fouling ballast.

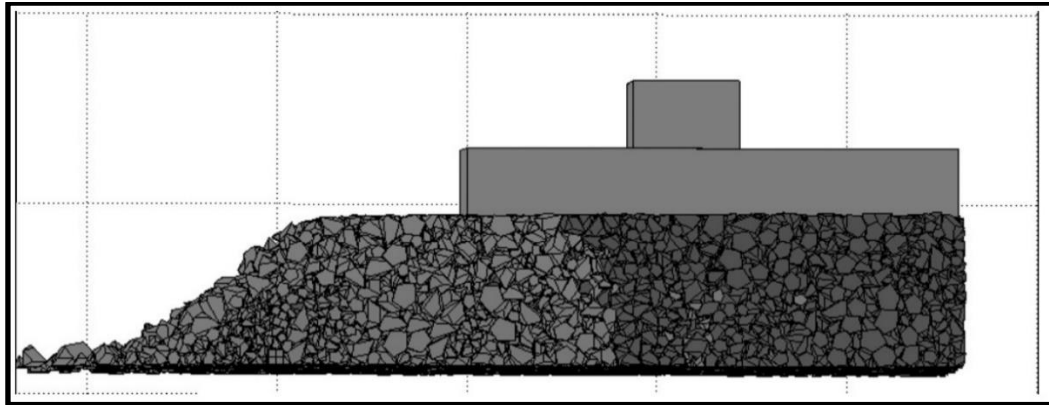


Figure 2.0-17. Example of DEM applied to investigate different scenarios of fouling ballast (Huang and Tumumluer 2011).

2.7.2. Railway vehicle models

According to Nielson and Oscarsson (2004), when the non-linear peculiarities (characteristics) of the railway track structure are considered, the track parameters (properties) are not only an expression of frequency but also of amplitude of the wheel-rail contact force (load excitation). Building upon the frequency range of interest, distinct levels of details of the vehicle model should be added in the simulation of train-track interaction. Knothe and Grassie (1993) investigated the vehicle dynamics concluding that they are influenced by frequencies below 20 Hz, and that at higher frequencies, a rigid wheel-set model can adequately perform the excitation of the track vertically as the unsprung mass (compounded of the wheelset) is its main contribution. In turn, above 50 Hz (the mid- and high-frequency range), Popp et al. (1999) indicate that simple rigid multi-body models are satisfactory for the modelling of the bogie and the car body as their dynamic behavior is decoupled by primary and secondary suspensions.

Additionally, Costa (2016), Costa et al. (2017), and Melo et al. (2022) suggest that to investigate the dynamic effect of a heavy-haul railway vehicle, the two adjacent bogies can represent the greatest load solicitation because of superposition that the wheel loads cause into the railway track. Furthermore, as usual in many multi-body simulation software, the rigid-body depictions (e.g., mass, moment of inertia, and position of centre of gravity) of the car body, the bogies, and the wheel-sets are generally applied; spring and damper elements (suspension elements) are adopted to couple the wheel-set and the bogies, and the bogies and the car body.

Railway vehicle-track models are now developed in 3D, and they are efficient in forecasting highly dynamic linear and non-linear conditions. Today, there are several commercial FE software packages available that allow models to be constructed more efficiently for general analysis. These include ABAQUS, LS-DYNA, ANSYS, etc.

2.8. Summary

This chapter explain the conception of a heavy-haul ballasted railway track and describes its key track components (rail, fastening system, ballast, sub ballast and subgrade) – including some of their static and dynamic properties, limitations and assumptions – as well as the usual track geometric elements (gauge, vertical levelling, lateral alignment, twist, and cant) and the different methodologies (statistical, vehicle response, and frequency analysis) to assess them. Also, it explains the railway vehicle-track interaction mechanisms describing a heavy-haul unpowered vehicle and its components (car body, bogies, suspensions, and wheelset). Moreover, it identifies the main forces that usually act on a track influencing particularly the track geometrical degradation. Furthermore, the Chapter 2 explains the general railway operational conditions that significantly affect the track geometrical degradation under cyclic

loadings. Lastly, it describes the different methodologies (limitations and assumptions) to model a ballasted railway vehicle-track system. It is possible to note based on this literature review that the range of the track and vehicle components parameters can be a challenge to model properly a railway vehicle-track system, specifically to investigate the track geometrical degradation phenomenon.

To understand how the researchers worldwide have applied the different concepts and methodologies to model and to study the track geometrical degradation process, their findings and knowledge gaps, a complementary critical literature review will be presented in the following chapter (Chapter 3).

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A REVIEW OF RAILWAY TRACK GEOMETRICAL DEGRADATION MODELS

This chapter provides a literature review regarding railway track geometrical degradation under investigation. Also, it presents and discusses the different methodologies – their findings and knowledge gaps – that have been applied so far to predict track geometrical degradation over different railway track conditions (dynamic forces) such as smooth track (no track geometric irregularities), unsupported sleepers track (hanging sleepers), and uneven track (track with geometric irregularities).

3.1. Ballasted Railway Track Geometrical Degradation Concepts

Under the influence of dynamic railway track loads, the track geometry degrades rapidly over time (Esveld 2001). Knowing about the track geometrical degradation process will support the maintenance activities of predicting the future state of a railway track geometry, (2) estimating the cost to keeping track of track geometry, and (3) extenuating the issues associated with railway operational safety.

The mechanism governing the railway track geometrical degradation is a complex process involving several influencing parameters such as train velocities, axle loads, track components parameters, maintenance processes, vehicle components parameters, and environment (Esveld 2001, Profillids 2006, Lichtberger 2011, Tzanakakis 2013, Berawi 2013). In turn, if a ballasted railway track is recently tamped, it is well-known that directly afterwards relatively large settlements occur due to unequal ballast settlements affecting the track geometric elements, particularly the vertical levelling. If every point of the railway track were

to settle by the same amount, no irregularities would develop (Esveld 2001), then the track is characterized as a smooth track; however, these settlements are often far from uniform due to inhomogeneities in support conditions such as the occurrences of (Hawari and Murray 2008, and Zakeri et al. 2015): (1) unsupported sleepers (US), and (2) initial track irregularities (ITI). When a local vertical profile loss varies along the railway track, vertical levelling irregularities develop further in a vicious cycle causing an amplification of the dynamic loading of track due to vehicle-track interaction. This results in differential settlements, which lead to the development of irregularities in the wavebands experienced by the train vehicles (Esveld 2001).

In the past and recent years, some researchers carried out appropriated and interesting literature reviews related to both railway track components deterioration and railway track geometrical degradation models. Conceptually, Melo et al. (2020) explain the term ‘track components deterioration’ as a general term to describe the physical (mechanical) deterioration of each individual component in railway track. In other words, it is what, how, when, and how much the component with a specific composition, form, and dimension loses its railway track function. According to Guler et al. (2011), it is difficult to use a single descriptor to capture all deterioration modes. On the other hand, the term ‘track geometrical degradation’ is usually considered random by nature (Vale and Ribeiro 2014) and applied to characterize the quality (condition) of track geometry by evolution over time (or tonnage) of one or several geometric elements such as longitudinal level, lateral alignment, gauge, twist, and cross level. In another definition, it is what, how, when, and how much one or more than one geometry element in a finite space into the railway track fails to maintain their known standard characteristics (Melo et al. 2020).

On that ground, Ferreira and Murray (1997) investigated the real factors that can influence on track geometrical degradation. They argued that the inferior state (downgraded) in

the railway track quality is chiefly driven by three conditions: (1) axle load, (2) train velocity, and (3) dynamic forces. According to Ferreira and Murray (1997), train velocity contributes to the track geometrical degradation process by escalating the dynamic forces at high train velocities and reducing those at low train velocities. Axle load contributes not only to increase rail and wheel wear and fatigue, strains and cracks in rail and sleepers, loosened fastening system, but also to intensify the ballast settlement (compaction of ballast and the fracture of ballast stone) due to the amplification effect of dynamic loads. These situations will also lead to increase railway track components deterioration (Berawi 2013). Figure 3.0-1 indicates the influencing parameters that may affect the geometrical degradation of a ballasted railway track.

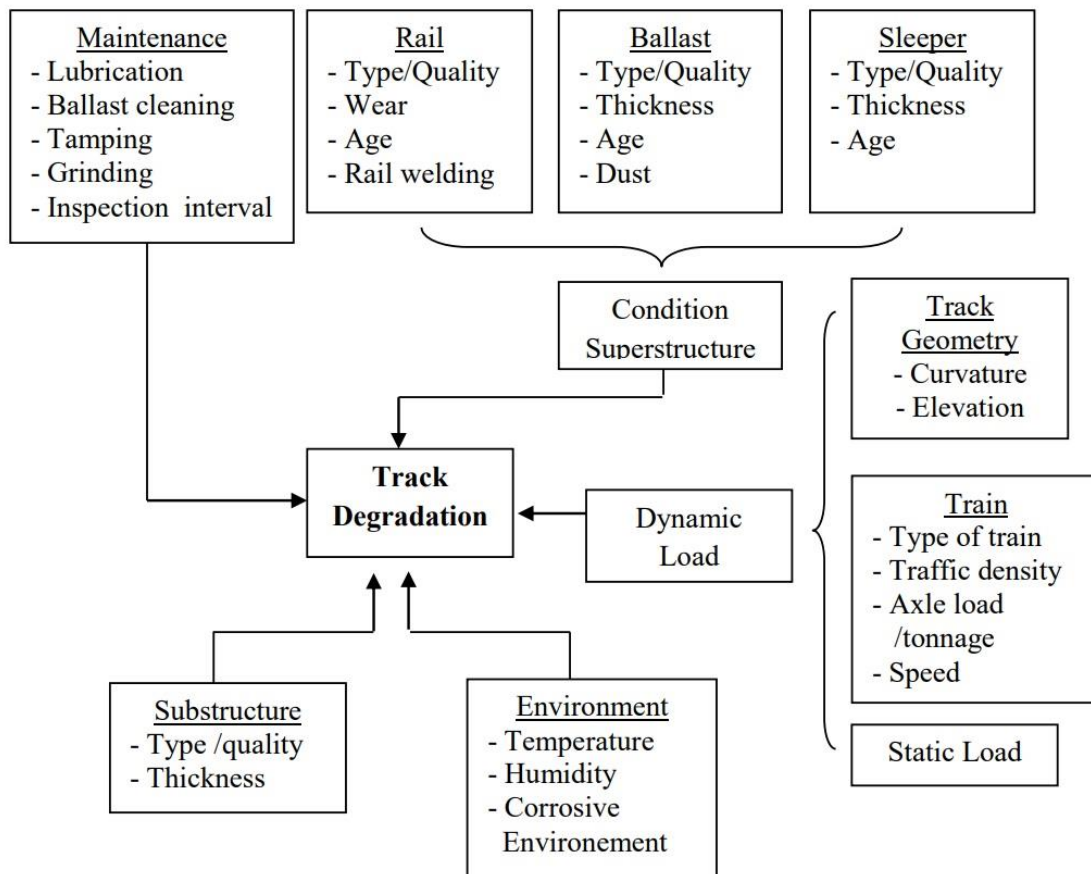


Figure 3.0-1. Influencing parameters that may affect the geometrical degradation of a ballasted railway track (Ferreira and Murray 1997).

3.2. Ballasted Railway Track Geometrical Degradation Curve

Figure 3.0-2 illustrates a schematic representation (general trend) of the progress of a track geometric element in a railway track geometrical degradation model. When the intervention threshold (the point in time at which degradation affects vehicle behaviour) is achieved, the track is tamped, and the standard deviation of the track geometric irregularities decrease (Lichtberger 2011). To specify where the geometric element limit is and to determine when the intervention is recommended, it is essential to understand the degradation behaviour of the track geometric element. Typically, the degradation line will exhibit a ‘saw-tooth-like’ line, in which the track geometric element quality degrades between two subsequent maintenance activities or post-construction (Jovanovich 2004).

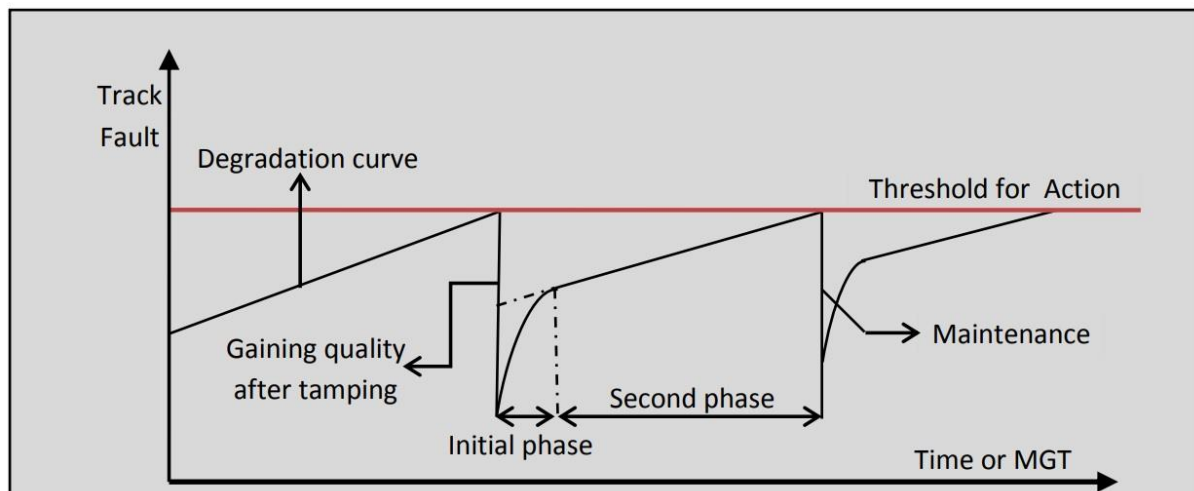


Figure 3.0-2. Schematic representation of a track geometric element applied to a hypothetical railway track geometrical degradation model (Lichtberger 2011).

A ballasted railway track is set up with an initial track geometric condition from a previous maintenance activity or freshly constructed segment. According to Lyngby (2009), directly after tamping a railway track segment, the track geometric element defects increase

rapid around the first 0.5-2 MGT until the gaps between the ballast stones have been decreased (ballast compaction) and the ballast is stabilized.

During that time, usually called the 1st phase of track geometrical degradation, the track quality commences to degrade because of interaction of various actual factors, such as the cumulative traffic loads (in number of cycles or in MGT), train velocity, and dynamic forces, etc. This period is followed by an escalating track deterioration, characterized by the ballast settlements (further ballast compaction position) (Indraratna et al. 2011, and Lichtberger 2011).

Once the track has been adequately stabilized, the second phase of railway track geometrical degradation appears. The geometric element quality will decay slowly and increase in linear proportion to the number of cyclic loadings (Lyngby, 2009). According to Indraratna et al. (2011), Lichtberger 2011 and Berawi 2013, various mechanisms of not only ballast but also railway track infrastructure components (e.g., sub ballast and subgrade) behaviour are governed during this process, such as ballast particle rearrangement, breakage, and abrasion and sub ballast or subgrade penetration into ballast pockets and voids implying in continuous settlements (Selig and Waters 1994, Li et al. 2016, Indraratna et al. 2011, Berawi 2013, and Guo et al. 2022).

Upon the track geometry irregularities achieve the threshold limit, tamping should be executed again to reduce the amount of standard deviation (e.g., vertical levelling in a track segment), leading the track geometric element to degrade in those two major phases as aforementioned. Afterwards, the performance of tamping will decline in time reducing the period between two maintenance activities. At that point, the tamping process is not recommended and, to repair the geometric defects, a track (re)construction should be provided.

3.3. Predictive Models of Railway Track Geometrical Degradation

Many investigations have been carried out on the fundamentals of the track geometrical degradation mechanism and the efforts not only to address the degradation issues but also to identify the contribution of each parameter (or element) to the integrated process (Melo et al 2020). It permits different possibilities of controlling the phenomenon of track geometrical degradation via existing or enhanced practical maintenance guidelines (Melo et al. 2022).

Dahlberg (2001) carried out an outstanding critical literature review regarding ballasted railway track settlements in smooth tracks (no track geometric irregularities). They observed that most models were used to describe the long-term behaviour of a railway track focused on the number of loading cycles (or MGT) and on the elastic track deflection caused by that load. However, the elastic deflection of a ballasted railway track has not necessarily any effect on the vertical levelling loss, which implies that instead of elastic deflections of the railway track, plastic deformations of the railway ballast and track infrastructure (e.g., sub ballast, and subgrade) should be modelled considering a yield 'limit' force.

Berawi (2013) also presented an interesting literature review related to track degradation models, in which they identified that the models were built up from the simple one that depended on a single element (or parameter) to an extensive one which considered various (some of them, empirical) influencing variables applied to a specific track segment under investigation. These models were classified into two different viewpoints (Sadeghi and Asgarinejad 2007): (1) structural (smooth track), and (2) geometrical (track irregularities). The 1st one was developed underpinned on the evolution of failures in the physical track structure components, such as rail wear and corrugation, and ballast settlement, and did not consider any initial track geometric irregularities. Shenton (1985), Chrismer and Selig (1993), and Sato (1995) have developed models in this approach. In turn, the 2nd one viewpoint (geometrical)

considered the influence of the existing state of railway track geometrical condition using geometric elements, such as vertical levelling and lateral alignment. Bing and Gross (1983) were the precursors in developing this approach, which since then has been applied worldwide. It is important to note that, in fact, both approaches are connected and as pointed out by Berggren (2005), any deviation of the geometric elements is known mostly as a result from the railway track structural component issues.

Ngamkhanong et al. (2017) and Ngamkhanong et al. (2018) carried out excellent critical literature reviews about track degradation discussing modelling and monitoring ballast and track resilience, respectively. In these reviews, they discussed, similarly to Bewari (2013), the limitation for the track geometrical degradation models proposed by Alva-Hurtado and Selig (1981), Shenton (195), and Sato (1995), and highlighted the improvements provided by Tutumluer (1995), who applied realistic ballast properties obtained experimentally. Also, they emphasised the advanced modelling developed by Ricci et al. (2005) and Gallego et al. (2011), which simulated ballast, sub-ballast, and subgrade in a FE (Finite Element) 3D package software to assess the performance of railway track under passing railway vehicle with great result in a whole track segment. Moreover, they highlighted the importance of the ballast on track geometrical degradation and discussed the advantages and disadvantages in modelling the railway ballast using a continuum or a discrete model. In case of the heavy-haul or high-speed train, which can cause ballast breakage and damage to the infrastructure components, Ngamkhanong et al. (2017) recommended to consider appropriately the nonlinearity of material. They indicated that to evaluate the track geometrical degradation overall the continuum model is the best option due to reducibly computational time and approachable results. Furthermore, Ngamkhanong et al. (2017) highlighted the importance of considering distinct factors related to train weight (axle load), train velocity, and dynamic impact load in

modelling a track geometrical degradation process to provide a general, practical, and reliable prediction model.

Soleimanmeigouni et al. (2018), Elkhoury et al. (2018), Higgins and Liu (2018) presented interesting and extended literature reviews regarding track geometrical degradation models, particularly because they decided to classify the models into different approaches: (1) mechanistic, (2) statistical (empirical), (3) mechanical-empirical, and (4) artificial intelligence. According to Zhang et al. (2000), the mechanistic approach comprised establishing, by theory or testing, the mechanical properties of railway track structure including the calculation of forces and displacements to evaluate the geometrical degradation of the rail (Elkhoury et al. 2018). Sato (1995) and Lyngby (2008) have established models following this approach based on Japanese and Australian experiences, respectively. These types of models can be challenging due to the difficulty of understanding the affecting variables of railway track structure components (e.g., railway ballast settlements) and high time consuming. Few recent investigations have been found on mechanist models, which indicates clearly the need for further studies. Statistical models, on the other hand, have been extensively used to predict railway track geometrical degradation. They are based on observations of the railway track geometry and the influencing factors, such as railway traffic, track components and maintenance activities; thus, they can simulate real-life states with mathematical equations to predict the future behaviour of railway track and its degradation (Elkhoury et al. 2018). Also, statistical models can identify the relationship between the factors affecting railway geometrical degradation and the condition of the railway track using a linear relationship (Esveld 2001, and Guler et al. 2011), even though some studies have found a non-linear relationship based on other forms of the model, such as polynomial, logarithmic, exponential, and multi-stage linear (Javanovic 2004). A statistic model was proposed by the Office for Research and Experiments (ORE) of the International

Union of Railways (UIC), in which they studied the fundamentals of the railway track degradation mechanism in the 1980s (Dahlberg 2001) indicating the importance of railway traffic, dynamic axle load and train velocity in affecting the geometrical degradation.

Following the literature reviews from the previous paragraph, mechanical-empirical models are a combination of mechanical and statistical models based on an understanding of the behaviour of railway track components, together with explicit observations, measurements, and large-scale data records. Sadeghi and Askarinejad (2010) conducted comprehensive research to improve current railway track geometrical degradation modelling techniques by applying thorough field investigation. In this approach, the main parameters that affect the rate of track geometrical degradation are grouped into three categories: (1) track structure indices (TSI), (2) track quality indices (TQIs), (3) average train velocity, (4) traffic parameters (in MGT), and (5) maintenance parameters. This approach, however, is limited as, to increase its accuracy, it requires further data records from monitoring activity. Finally, Artificial Intelligence (AI) model (i.e., Artificial Neural Networks – ANNs and Neuro-Fuzzy Logic – NFL, a combination between ANN and fuzzy logic), also considered in some literature reviews as an empirical model, is a modern tool that has increasingly been applied among researchers worldwide being recognized to have high predictive accuracy (Elkhoury et al. 2018). In multi-layered neural networks, the neurons are arranged in a layered fashion. The input and output layers are separated by a group of hidden layers in which the layer-wise architecture of the neural network is referred to as a feed-forward network (Aggarwal, 2018). Shafahi and Hakhamaneshi (2009) and Guler (2014) modelled railway track geometrical degradation with ANN. They considered the variables involved in geometrical degradation producing important findings on the relationships between the rate of degradation and independent variables.

Recently, Melo et al. (2020) presented a systematic literature review related to methods to monitor and evaluate the deterioration of track and its components. They identified, evaluated, and classified more than 100 different studies that predicted the process of railway track deterioration (track components) and railway track degradation (geometric elements). They classified the models into two diverse groups according to the tactic adopted: (1) model type, and (2) kind of approach. The model type could be: (1) statistic (empirical), (2) mechanistic, or (3) empiric-mechanistic; in turn, the kind of approach could be: (1) observable, (2) experimental, (3) numerical, and (4) hybrid (numerical-experimental or numerical-analytical). The data revealed that despite of a wide variety of methods, mostly studies focused on an observable approach (recording car data) of the railway track geometric elements, supported by statistic model, with a low degree of validation. Based on a target model, they proposed that a hybrid method could be chosen as a best option once it could consider the interactions between railway track components and geometric elements through a complex mathematical calculation (numerical analysis). Therefore, they tried to demonstrate that by using technological advances in computational methods (FE analysis) and by incorporating those techniques, it can be possible to fill the current gap in modelling and create models that permit multiple processes leading to railway track geometrical degradation (Melo et al. 2020). Figures 3.0-3 and 3.0-4 illustrate, respectively, the classification of the studies evaluated and the established and potential tactics in evaluating track deterioration and its 'elements', both indicated by Melo et al. (2020). Table A.1 in Appendix A presents a summary of the different strategies adopted to carry out the literature reviews regarding railway track components deterioration and geometrical degradation so far.

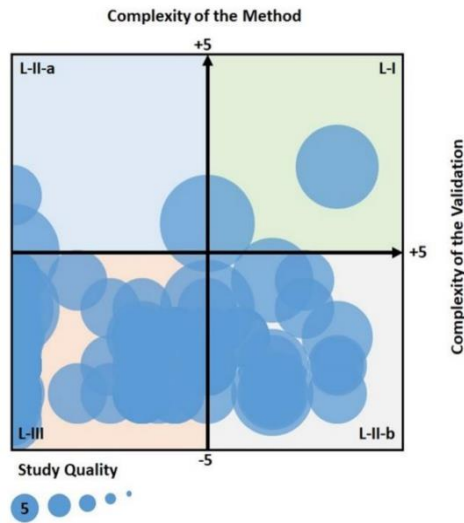


Figure 3.0-3. Study groups in according to the complexity of the validation, the complexity of the method, and the study quality (Melo et al. 2020).

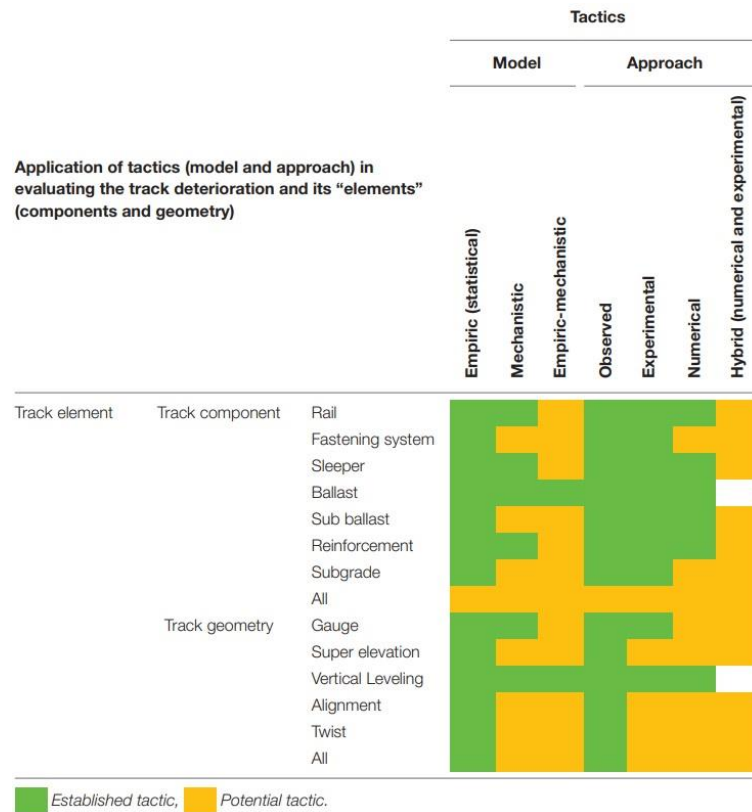


Figure 3.0-4. Application of tactics (model and approach) in evaluating the track deterioration and its 'elements' (components and geometry) (Melo et al. 2020).

3.4. Track Geometrical Degradation in Smooth Tracks

According to Melo et al. (2022), an important contribution to the track geometrical degradation is the differential track settlement, which impacts directly on the spatial position of the rail track, defined as vertical levelling (VL). As it is one of the most important tracks geometric elements representing more than 50% of geometric irregularities in a ballasted railway track (Soleimanmeigouni et al. 2018), this investigation focuses on that track geometric element. Moreover, a poor VL means a poor ride quality and excessive dynamic forces for track and vehicles components, and the inevitable result is a less efficient, less popular, and more costly railway (Thom and Oakley 2006, and Melo et al. 2022).

Also known as vertical profile or longitudinal level, the VL is described in BS-EN-1348-16 as the deviation of consecutive running table levels on any rail, expressed as an excursion from the mean vertical position as aforementioned in Chapter 2. Any weakness in the railway track support system (track components) will affect negatively the railway track vertical profile increasing its loss, which is usually known as vertical levelling loss (VLL) (Melo et al. 2022).

In principle, track geometrical vertical levelling loss (VLL) is defined as a parameter of how much the rail loses its vertical position in the track physical space (Melo et al. 2022). In general, it can be described to occur in two distinct phases before the first railway maintenance activity: (1st) a rapid consolidation of the railway ballast directly after track construction or maintenance, and (2nd) a slower loss rate related mostly to ballast settlement (Selig and Waters 1994, Nguyen et al. 2016, and Melo et al. 2023a). At this 2nd phase, the rate can be approximated by a linear deterioration with the logarithm of the number of cyclic loadings or million gross tons (MGT) as the rate of ballast plastic deformation decreases gradually (Melo et al. 2023a). This is in accordance with Indraratna et al. (2011) who describes that the rate of ballast plastic

deformation decreases gradually as cyclic loadings increase also indicating a logarithmic behaviour for VLL. As the ballast has the largest influence on track settlements according to Selig and Waters (1994) and Nguyen et al. (2016), this investigation also pays special attention to that track component. Additionally, over a long term, there are further settlements due to ballast particle rearrangements and particle breakdowns as well as penetration of sub ballast and subgrade into ballast voids and inelastic recovery of subgrade at unloading (Nielsen and Li 2018). Moreover, as highlighted in Kempfert and Hu (1999), Esveld (2001), Sun (2015), and Mezher et al. (2018), the railway track structure and its components, particularly the ballast (however, it can also be extended to the sub ballast and subgrade), play a key role in being dynamically affected by the load travelling velocity and, consequently, having a different amplification of its displacement depending on how it vibrates naturally. In other words, the natural frequencies in which a specific track vibrates influence on how much the ballast defects under a specific train velocity (Zakeri et al. 2016, Zakeri et al. 2017a, and Zakeri et al. 2017b) over time, which can negatively affect its critical train velocity.

Several VLL predictive approaches have been derived empirically (directly or indirectly) from laboratory (triauxle, reduced scaled box or full-scale box tests) and field experiments, by various researchers worldwide, mostly focusing on ballast settlement. Dahlberg (2001) carried out an excellent critical review, which was mentioned by Thom and Oakley (2006), and updated and well-illustrated recently by Grossoni et al. (2019). Figure 3.0-5 summarizes the comparison of these approaches graphically. It can be noted that those VLL investigations are presented within three different ranges of initial ballast compaction: softer, medium, and stiffer, respectively, '1–5 mm', '5–10 mm', '> 10 mm', for 900 thousand cycles (Melo et al. 2022). However, based on that updated review, it is possible to infer that there is not a consensus among the experimental conditions under which the experiments were

performed and, hence, among the results. This means clearly that there is a research gap related to the specification of numerical and field (or laboratory) experiments to coordinate or harmonize the VLL predictions. Moreover, mostly empirical methods indicate a dependency exclusively on the number of cycles without considering any different operational, environmental, vehicle, and track conditions. To address those two knowledge gaps identified, Melo et al. proposed the development of a new hybrid numerical-analytical method considering railway dynamic conditions.

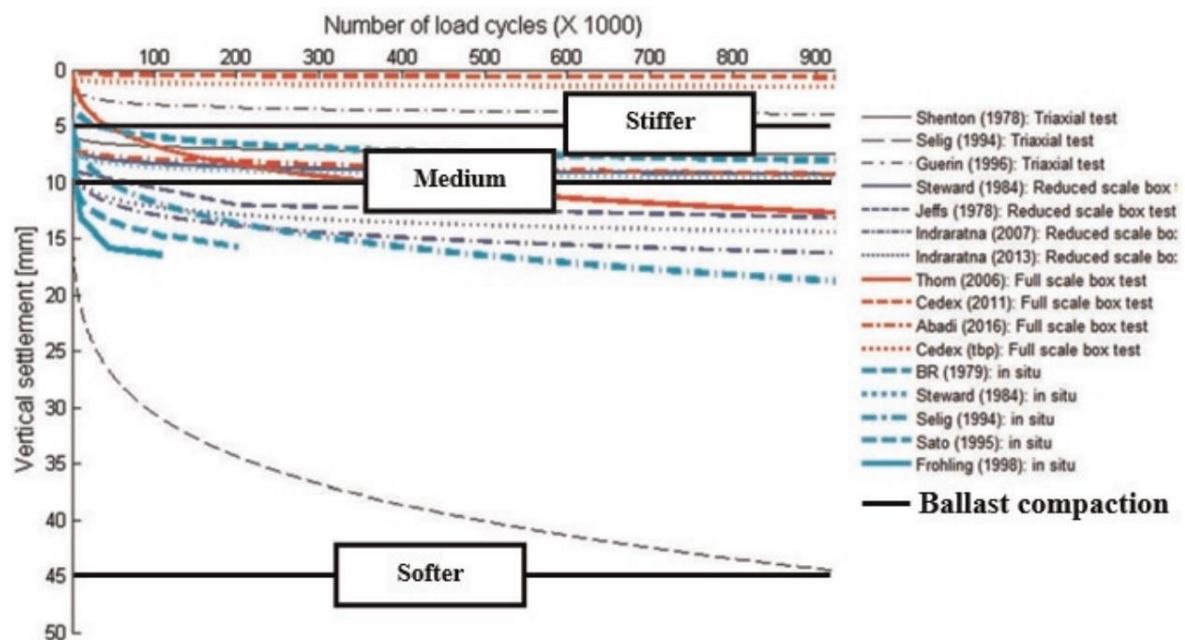


Figure 3.0-5. Comparison of ballast empirical settlement predictive laws from laboratory and field experiments (Grossoni et al. 2019, and Melo et al. 2022).

Based on the literature reviews previously described the development of a new hybrid method to predict track geometry VLL can be extremely useful for filling the current knowledge gap (especially when considering the global train-track dynamics). Also, this innovative

approach can support the enhancements of planning, decision-making and maintenance activities. According to Blair and Chan (2006) and Higgins and Liu (2018), different approaches of track degradation models have been continuously developed over the past few years, however there are still many vehicle-track-related issues that are not fully understood. The plastic deformation and nonlinearity of material properties, the effect of initial track geometric irregularity effect, and the contacting surfaces, under cyclic loadings, are some of these issues to be addressed as also identified by Melo et al. (2020) and highlighted in Melo et al. (2022). Appendix B presents a summary of different railway ballast settlement models in smooth tracks obtained from different literature reviews related to track geometrical degradation.

3.5. Track Geometrical Degradation in Unsupported Sleepers Tracks

In a railway track, ballast voids and pockets underneath the sleeper can occur due to unequal ballast settlements that may cause a gap between the ballast and the sleeper (Melo et al. 2023a). As a result, one or more sleepers can be partially unsupported from the rail as some parts of rail remain suspended causing a variation of dynamic force in the track section (Azizi et al. 2021a). In a poor vertical profile, large gaps can be readily observed between the sleepers and the ballast (Zhu et al. 2011, and Zakeri et al. 2015). Furthermore, considering in situ measurements, Zhu et al. (2011), Zakeri et al. (2015), Olsson et al. (2002), Augustin et al. (2003), and Sresakoolchai and Kaewunruen (2022) indicated that small lacks between the ballast and the sleepers were very recurrent at an ordinary railway location (over 50%).

The dynamic forces caused by unsupported sleepers (US) are responsible for escalating the VLL under dynamic cyclic loadings, for example, by damaging the track components, particularly the railway ballast. When a local VLL varies along the railway track, VL

irregularities develop further in a vicious cycle causing an amplification of the dynamic loading of track due to vehicle-track interaction (Melo et al. 2023a). Also, as highlighted in Kempferm and Hu (1999), Esveld (2001), and Sun (2015), the natural frequencies (or wavelengths) of a railway track structure (and components) influence on how much it vibrates under a specific train velocity (Zakeri et al. 2016, 2017a, and 2017b), after innumerable cyclic loadings, which can negatively affect how much it deflects (Sresakoolchai and Kaewunruen 2022). Moreover, because of high flexible stiffness of rail, the rail vertical displacements and their reactions on the adjacent sleepers are aggravated. Therefore, a reasonable physical understanding about the effect of US on VLL is of great interest for supporting the prediction of the long-term track geometrical deterioration by assessing the current track components or introducing new ones. Figure 3.0-6 illustrates schematically the concepts of US effect on VLL in a ballasted railway track.

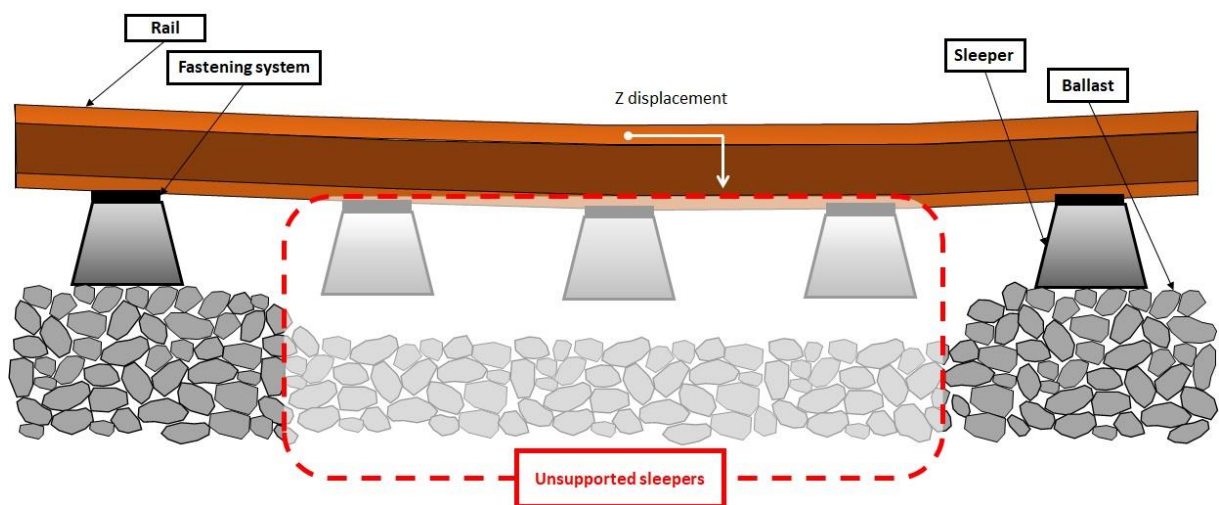


Figure 3.0-6. The concept of US effect on VLL in a ballasted railway track (Melo et al. 2023a).

In the past and recent years, a vast number of researchers have investigated the track settlements and have proposed different approaches to predict the track geometrical VLL,

mostly focusing on ballast settlement as before-mentioned (Melo et al. 2020, and Melo et al. 2022). Dahlberg (2001), Thom and Oakley (2006), and Grossoni et al. (2019) carried out an excellent critical review revealing that there was not a common proceed among study conditions and, hence, among their results. Besides, the methods indicated a dependency only on the number of cyclic loadings without considering different operational, vehicle and track conditions. Trying to address the research gaps identified, Melo et al. (2022) proposed a new numerical approach considering the railway dynamics conditions. However, the novelty suggested by Melo et al. (2022) does not contemplate the effect of US on VLL (Melo et al. 2023a).

Based on an extended literature review, it has been observed that no other researchers have studied the dynamic effect of US on track settlement, particularly on VLL under cyclic loadings, considering different operational conditions and elastic-plastic behaviour of track components. Research discusses dynamic responses of traditional US track (the ballast is removed beneath the sleepers) under monocyclic loading (Melo et al. 2023). In the past, Grassie and Cox (1984) examined experimentally that on traditional US track, the dynamic wheel-rail contact force can be up 80% higher than on well supported track for monotonic loading. SUPERTRACK (2005) performed a numerical modelling of railway track introducing gaps of 0.5 mm and 1 mm under three cyclic loadings and ballast plastic behaviour indicating that the sleeper-ballast contact force increases by 70% in the rail with a gap of 1 mm, similarly to the numerical study reported by Lundqvist and Dahlberg (2005). Zhang et al. (2008) also studied the effect of US on the normal load of wheel-rail through a numerical simulation and their results show that the gaps have a huge response on that force as the fluctuating amplitude increases for a categorical number of US when the train velocity increases, particularly when the number of traditional US reached 5 or 6, which meant that the wavelength of the fluctuation

depends on the excited resonant frequencies of the vehicle-track system. Bezin et al. (2009) studied the cant deficiency effect of rail on the railway tracks with US by using numerical modelling showing that the presence of US increases the ratio (lateral/vertical force ratio) by 3%-8%. Zhu et al. (2010), Zakeri et al. (2015), Zhang et al. (2016), Mosayebi et al. (2017), and Dai et al. (2018) also performed numerical simulations suggesting that the train velocity, the gap range, and the number of US primarily impose the magnitude of impact load, which is significant at high speed, whereas such impact at low speed is insignificant. Zhu et al. (2011) investigated the effect of traditional US on the track dynamic characteristics by experiments indicating that since the US leads to a discontinuous and irregular track support, the wheel-rail dynamic interaction is excited being increased as the number of US is increased, or the train velocity is raised.

Recently, some researchers have worked on numerical modelling and experiments, however, despite of interesting findings – similarly to the previous studies, none of them presents any findings regarding the effect of US on VLL under cyclic loadings (Melo et al. 2023a). The studies mostly continue to focus on monotonic loading and elastic behaviour of the track components. Ienaga et al. (2016) carried out numerical simulation and experiments under low-speed range to investigate the effects of traditional US identifying an increase in rail displacement when the vehicle passes over the section with reduced track support stiffness. Sadeghi et al. (2018) also researched the response of traditional US using an improved 3D numerical model and experiments indicating that an increase in the gap size (0.4 mm) results in intensification of the sleeper-ballast contact forces (25%) in the single US and that any increase of the gap of more than 0.4 mm causes negligible changes in the sleeper responses (5%). Sysyn et al. (2020) carried out experimental and numerical investigation to study the dynamic interaction between the wheel and the rail with US showing that there exists a critical gap size

around 2.5 mm for four US, which causes the largest force variation. Azizi et al. (2021a), Azizi et al. (2020), and Azizi et al. (2021b) also investigated numerically and experimentally the response of train velocity in displacement of a ballasted railway track with traditional US finding that the velocity of the vehicle on the track displacement with less than 4 fully US has no effect, but by increasing the number of US, the effect of increasing velocity is considerable.

Sresakoolchai and Kaewunruen (2022) proposed an innovative prognostic to detect and identify severities of US using machine learning based on a verified numerical simulation with existing field measurements. Differently from the others, Augustin et al. (2003) investigated numerically and experimentally the influence of inaccurately positioned sleepers on track settlement under cyclic loadings testing on the ballast a cross-shaped footing made of concrete. They identified without distinguishing that badly placed sleepers significantly influence the evolution of track vertical displacements.

In general, as described above, no other studies provide an accurate investigation of the effect of US on railway track VLL in a long-term behavior. On this ground, to address the knowledge gap identified, this study proposes the development of a novel improved numerical method to predict track geometrical VLL considering not only the railway dynamic conditions but also the response of US under load cycles (Melo et al. 2023a). Appendix C summarises the techniques proposed by each track geometrical degradation method to predict the effect of US on VLL.

3.6. Track Geometrical Degradation in Uneven Tracks

The dynamics forces caused by initial track irregularities (ITI) are responsible for expanding the VLL under dynamic cyclic loadings, for example, due to compaction of ballast and fracture of ballast stones (Melo et al. 2023b). Also, the natural wavelengths (or frequencies) of a railway

track structures (and their components) influence on how much it vibrates under different train speeds (Kempferm and Hu 1999, Esveld 2001, Sun 2015, Kaewunruena et al. 2018, and Kaewunruena and Ngamkhanonga 2020) affecting negatively on rail vertical displacements and their reactions on the adjacent sleepers (Kaewunruena et al. 2019, Sadeghi 2020, and Melo et al. 2022). Therefore, a reasonable physical study about the effect of initial track roughness on VLL is of considerable interest for supporting the prediction of the long-term track geometrical degradation. Figure 3.0-7 shows schematically the concepts of the influence of initial track geometric irregularities on VLL in a ballasted railway track.

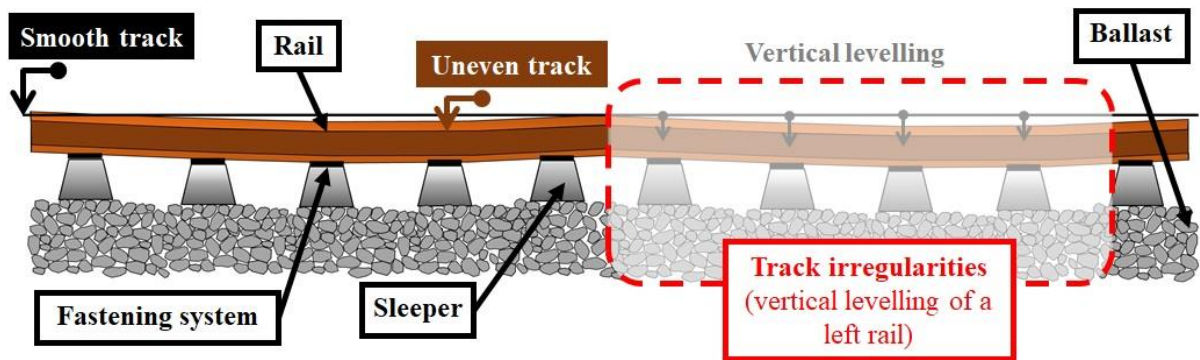


Figure 3.0-7. The concept of the influence of initial track geometric irregularities on VLL in a ballasted railway track. (Melo et al. 2023b).

For the past three decades many researchers have investigated the track settlements in a smooth track (without track geometry irregularities) and have proposed different approaches to predict the track geometrical VLL, mostly focusing on ballast settlement, as pointed out by Melo et al. (2020) and Melo et al. (2022). Dahlberg (2001), Thom and Oakley (2006), Berawi (2013), Abadi et al. (2016), and Grossoni et al. (2019) carried out outstanding literature reviews revealing that there were not typical proceeds among investigation conditions and their outcomes. Also, mostly methods indicate dependency only on the number of cyclic loadings

without taking into consideration any difference into railway dynamic conditions. Trying to address the investigations gaps, Melo et al. (2022) suggested a new numerical-analytical approach considering operational, vehicle and track conditions. However, the innovation proposed by Melo et al. (2022) does not foresee the effect of ITI on VLL.

Based on a continued literature review, it has indicated that no other studies have investigated the dynamic effect of ITI on VLL under cyclic loadings considering different operational conditions and elastic-plastic behaviour of track components. The research examined dynamic responses of track irregularities between maintenance interventions in a specific site and under a particular railway condition.

In the past, Partington (1979) studied experimentally in laboratory that on ITI, the VLL was affected after one thousand passes (or cyclic loadings) in the case of the high average lift (after tamping) for the low load tests. Suiker and Borst (2003) performed a numerical modelling of railway track suggesting that dynamic effects of track irregularities can be considered by introducing the dynamic responses to instantaneous train axle load into one or more dynamic amplification factors, which may serve as multipliers for the quasi-static force applied in the performance of long-term track degradation. Augustin et al. (2003) also studied the effect of ITI on VLL. They concluded that an initially strong deviation led to large height differences as the discrepancies of loss were more extreme in the case of great initial height variance. Takemiya and Bian (2005) studied distinct characteristics of layered subgrade and moving axle loads, which led to significantly dispersive response features, depending on the train velocity: (1) quasi-static for a low velocity, and (2) dynamic for a high-speed situation. Hawari and Murray (2008) investigated experimentally in three sites the relationship between the standard deviation (SD) of roughness of a railway track segment and the rate at which the vertical profile geometry of that track segment deteriorated indicating that there was a threshold

of about 0.7 mm of roughness below which the rate of deterioration is small. Chang et al. (2010) performed field experiments and they considered that total passing tonnage was the main influential factor when predictions were made for the changes of vertical profile irregularity level over a specific unit track section. Faiz (2010) investigated the effect of univariate and multivariate correlation analysis of track irregularities on the track dynamic characteristics by analytical predictions indicating that since the track irregularity can be aligned it led to minimize the predictive error of track degradation problems.

In the beginning of last decade some researchers carried out other investigations focused mostly on numerical analysis. Choi et al. (2012) conducted a numerical simulation research to investigate the influence of track irregularities with various wavelengths and amplitudes modelled using the VAMPIRE program on the running behavior of high-speed trains and to support the revision of the irregularity standards. They concluded that the vertical levelling irregularities had, particularly at long wavelengths, a strong influence on vertical vehicle acceleration. Berawi (2013)'s research found that there was a strong positive relationship between the left and the right rails in a longitudinal profile as they were similar for wavelengths longer than 6 m.

Guler (2014) decided to study the effect of track roughness modelling the railway track geometrical degradation with Artificial Neural Network (ANN), which produced a reasonable R^2 value (0.742) for vertical profile. Choi (2014) evaluated theoretically and experimentally the dynamic features of a ballast track revealing that the track impact force for the service track appeared to increase with the track support stiffness. Naeimi et al. (2015), employing a numerical modelling process, concluded that for the irregular rail cases, the dynamic responses of the consecutive sleepers appeared on a greater number of sleepers, while the static solution covered fewer sleepers. Moreover, Naeimi et al. (2015) highlighted that the results of dynamic

displacements for the consecutive sleepers in vertical profile confirmed the effect of irregularities on dynamic responses and that the differences were even further meaningful when the severity of the longitudinal irregularity (difference between the left and right vertical profiles) was increased. Shen et al. (2015) investigated the effect of vertical track irregularities on ballast settlement under few cyclic loadings indicating that the amount of settlement increased: (1) three times when train velocity increased from 60 km/h to 120 km/h, (2) rapidly when train velocity was more than 100 km/h, (3) by 38.6% as axle load increased from 25 tons to 30 tons, and (4) with increasing traffic as there was a linear relationship between amount of settlement and traffic.

For the last 10 years, some researchers have also worked on both numerical modelling and experiments to study the influence of track irregularities on vertical profile; however, despite of interesting findings, none of them presents findings related to the effect of ITI on VLL under both cyclic loadings and different track and operational conditions. The investigations mostly continue to focus on dynamic responses of track irregularities in a specific site and railway condition. Nguyen et al. (2016) studied numerically based on an empirical ballast settlement law the effect of track geometry defects under railway traffic cyclic loadings finding major influence of train velocity on the evaluation of vertical profile loss. Soleimanmeigouni et al. (2017) proposed a two-level framework to model the evolution of track geometry degradation over a spatial and temporal space using a simple linear model finding that the degradation parameters over the spatial interval may be generated by some Gaussian processes.

Nielsen and Li (2018) carried out a numerical investigation to study the dynamic interaction between the wheel and the rail with longitudinal level and empirical settlement of ballast/subgrade. They demonstrated that the track geometrical degradation over time was

caused by a prescribed initial rail irregularity; however, the settlement model did not explicitly account for the material properties and multiaxial stress-strain conditions in the track substructure or the interaction between different regions of the track substructure. Guo and Zhai (2018) also carried out numerical simulation based on an empirical power model for settlement prediction to investigate the effect of track subgrade settlement with a regular operation pattern. They concluded that, during a long-term track degradation, the ITI induced dynamic responses of the vehicle–track coupled system in terms of the wheel-rail interactions.

De Miguel et al. (2018) researched the response of track geometry irregularities by implementing an empirical settlement law and a multi-body simulation software (MBS) at 80-km/h train velocity. They showed that it was possible to assess the development of both the dynamic interaction forces between the vehicle and the track and the vertical track irregularities with low computational time compared to FEM. Grossoni et al. (2019) investigated analytically the role of track stiffness and its spatial variability through a set of computational experiments estimating the track geometry degradation rates. They suggested that the vertical track interactive model can calculate the evolution of the rail track irregularities under a particular cumulative empirical settlement law. Soleimanmeigounia et al. (2020) developed a data-driven analytical approach considering the occurrence of shock events and showing that the linear model was an appropriate choice for modelling the degradation pattern of longitudinal level defects.

Bednarek (2021) carried out a full-scale field experimental investigation and simulated the influence of short track geometry irregularities statically (no influence of train velocity) and with elastic parameters of the track components (no elastic-plastic deformation). They observed that the induced irregularity significantly changed the work of the loaded elements of the railway track structure increasing the rail deflections. Grossoni et al. (2021) suggested a semi-

analytical approach based on the known behaviour (empirical equation) of granular materials under cyclic loadings. It permits to capture the differences in the rate of development of permanent settlement because of the initial track bed stiffness.

Differently from others, Kosukegawa et al. (2023) recently proposed a method to forecast the vertical profile from track roughness taking into consideration exogenous factors and spatiotemporal correlations using a convolutional long short-term memory. They have found that linear regression may be enough if maintenance routine is lower; however, when maintenance operation is frequently required, spatial calculation and maintenance registries improve prediction significantly.

In general, as described above, no other studies have provided accurate and parametric investigation of the effect of ITI on railway track VLL considering the train-track interaction as a whole and: (1) long-term performance, (2) operational conditions (e.g. axle load, train velocity), (3) vehicle parameters (e.g. dynamic stiffness of 1st suspension), and (4) track parameters (e.g., dynamic elastic-plastic behaviour of railway ballast). On this ground, to address the revealing knowledge gap related to predict properly the dynamic influence of initial geometric defects on VLL under cyclic loadings and elastic-plastic behaviour of railway ballast, this research proposes the development of an innovative numerical-analytical method to predict track geometrical VLL considering not only the transient dynamic conditions but also the long-term effect of ITI under repetitive loading cycles over the service life. This approach can support the development of an efficient practical maintenance guideline recommending ITI thresholds for a minimum effect on VLL over time. Appendix D summarises the strategies adopted by each track geometrical degradation method identified that predicted the influence of initial track irregularities on VLL.

3.7. Summary

This chapter identifies several current and previous investigations based on an extended critical literature review including meaningful findings as well as conceptual and methodological contributions to the ballasted railway track geometrical degradation under heavy-haul cyclic loadings. Also, it presents, discusses, and summarizes the different methodologies – their findings and knowledge gaps – that have been applied to predict the track geometrical degradation over time and different circumstances (smooth tracks, unsupported sleepers track, and uneven tracks) including empirical, numerical, and experimental studies on dynamic vertical levelling loss of a ballasted railway track. It is clear underpinned on the literature review that there are many research gaps that have never been properly addressed needing to be fully filled to deal with not only the track geometrical degradation process itself but also to support the development of new track maintenance guidelines.

To fully understand the track geometrical degradation and the factors that can influence it, an innovative methodology will be proposed in the following chapter (Chapter 4). Moreover, the numerical-analytical approach (FEM-Regression Analysis – FEMRA) will be studied in Chapters 5, 6 and 7 to investigate, respectively, the VLL in smooth tracks, the effect of hanging sleepers track on VLL, and the influence of track irregularities also on VLL. Furthermore, in Chapter 5, the parametric studies related to VLL in smooth tracks will be investigated covering essential railway operational conditions.

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CHAPTER 4

METHODOLOGY

This chapter presents a general methodology to carry out the subject under investigation: numerical-analytical approach to predict ballasted railway track geometrical degradation under cyclic loadings and elastic-plastic behaviour of material (ballast) focused on vertical levelling track geometric element. Also, it presents the proposal of three innovative and complementary methodologies to predict vertical levelling loss (VLL) over different railway track conditions: smooth track (no track geometric irregularities), unsupported sleepers track (hanging sleepers), and uneven track (track with geometric irregularities).

4.1. Introduction

In the past and recent years, some researchers carried out interesting literature reviews and investigations related to track geometrical degradation as described in Chapter 3. Mostly researchers have focused on dynamic effect of monotonic load and elastic behaviour of material (including the railway ballast). In general, they have indicated that three factors drive the downgrade of a ballasted railway track in track geometry quality either post-construction or between maintenance activity: axle load, train velocity and dynamic forces. It means that the mechanism of track geometrical degradation is a complex phenomenon, particularly due to the dynamic forces caused by differential ballast settlements over time under cyclic loadings, which is an important contribution to the track geometrical degradation.

The dynamic forces caused by differential ballast settlements directly affect the track geometric vertical levelling (VL), which represents more than 50% of geometric irregularities in a ballasted railway track as before mentioned. In a track without track geometric irregularities

(smooth track), every point of the track settles by the same amount (no differential settlements occur) not causing any increase of dynamic forces except those due the natural frequency of track and vehicle components, individually or as a whole. On the other hand, in tracks with either hanging sleepers or initial track irregularities, the dynamics forces caused by them are responsible for escalating the track settlements under cyclic loadings damaging the track components, particularly the railway ballast, in a vicious cycle.

Recent developments in respect to FE (Finite Element) analysis algorithms and powerful computers (High Performance Computers – HPCs) enable researchers to rethink the modelling of a railway vehicle-track system and its deterioration and/or degradation processes considering different track, vehicle, and operational conditions of railways. One of potential strategies in promoting the vehicle-track modelling on FE is turning a time-dependent model to a must-have approach to complement conventional methodologies for predicting track geometrical degradation phenomenon.

4.2. Research Methodology

As aforementioned, this research aims to develop a robust and validated ballasted railway track models to predict track geometrical degradation over diverse track conditions (smooth, unsupported sleeper, and uneven tracks), focusing on the vertical levelling geometric element over time under cyclic loadings. The proposed models consider specific railway conditions (track, vehicle, and operation), while having been developed strategically to support different scenarios (parametric approaches). Figure 4.0-1 describe briefly the key phases propose to develop this research

The research begins by carrying out extended critical literature reviews (ballasted railway track and track geometrical degradation models) to address properly the research aim

and objectives (phases 1-5), as described in Chapter 1. The findings at the end of the literature reviews indicates clearly the gaps and limitations in past and recent methods, which support the review of research objectives and answer the research questions.

Following on Figure 4.0-1, the main part of this research is divided into 5 phases (6-10), both related to the three track conditions (smooth, unsupported sleepers, and uneven tracks). In phases 6 and 7, respectively, the research defines the methodologies underpinned on the gaps identified in phase 5 e proposes the design of the railway track-vehicle system to model the phenomenon and the track condition. In turn, phases 8-9 perform, examine, and validate rigorously the proposed models checking whether they can deal properly with the condition mapping innovatively under cyclic loading and elastic-plastic behaviour of the railway ballast. In phase 10, the research originally introduces the numerical-analytical approach concept through a complementary regression process to capture the trend of track geometrical degradation element (vertical profile) in a long-term behaviour.

The concept of vertical levelling loss (VLL) offers a transparent methodology to evaluate the consequences of different track condition effect on a key track geometric element: the vertical levelling (VL). It is important to note that the VL is identified as a critical and the most common track geometric issues in a ballasted railway track. Moreover, a track geometrical degradation model must have the ability to respond and exploit proactively any escalation of track geometric vertical levelling losses to support the decision-making in choose when and where to intervene preventively. Various scenarios have been proposed to identify any critical limitations in the modelling framework.

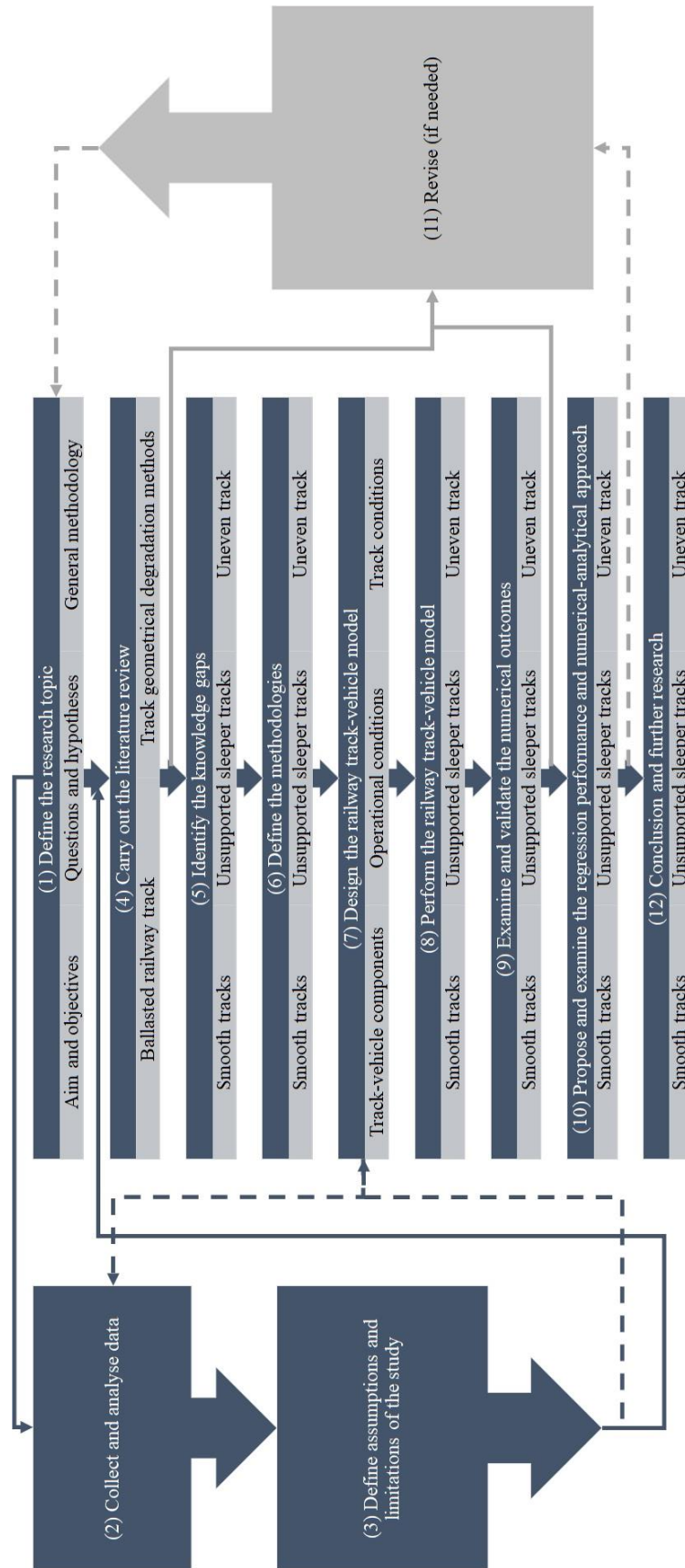


Figure 4.0-1. Research methodology flowchart.

4.3. Smooth Track Model

From the theoretical concepts, a ballasted railway track without any initial track geometric irregularities is described as a hypothetical smooth track, or a perfect track, or even a simply smooth track. This is because in ballasted railway track, despite being constructed in a high standard track geometric quality, it is impossible to guarantee after construction or maintenance activity (e.g., tamping) a perfect track geometry. In this case, the dynamic forces are limited to track, vehicle, and operational condition as the track geometric will not cause any issue on the dynamic wheel-rail contact area. Normally, a smooth track is defined to simplify field, laboratory and numerical experiments analysis being a good reference to investigate the material of track components. In those cases, the effect of any track geometric irregularities is not considered or, eventually, it can be considered empirically as an impact factor to be multiplied by static load, thus overestimate the forces acting in the track.

The numerical study in this research is performed considering the technical and operational characteristics of the Carajás Railway (EFC), one of the most important heavy haul railways in Brazil that is planning to transport more than 240 million tonnes of iron ore and soil bean. Its track has 1600 mm gauge and is composed by ASTM 136RE rail (weight: 68 kg/m), mono-block concrete sleeper (length: 2800 mm, height: 250 mm and width: 265 mm), spacing between sleepers of 610 mm, fast-clip fastening system and crushed rock ballast (height: 300 mm and shoulder: 300 mm).

In the EFC, the key railway vehicle is the GDE wagon of which the distance between axles and the adjacent bogies is 1828 mm and 2562 mm, respectively, considering this configuration of the bogies as the greatest load solicitation because of superposition that the wheel loads cause into the track (Costa 2016, and Costa et al. 2017). In this study, a straight segment is chosen as the initial focus is on vertical levelling of the track geometry. As diverse

types of finite elements (FEs) enable a variety of structures or components, the EFC's track can be modelled in both two and three dimensions (Melo et al. 2022).

Based on the typical track and vehicle components illustrated in Figures 4.0-2 and 4.0-3, respectively, and their dynamic parameters described on Table 4.0-1, the model is designed in 3D on LS-Dyna, a commercial FE software package, for modelling approximately 25 m of railway track and two halves of the typical wagon. The model is performed by applying both linear elastic and elastic-plastic behaviours of the materials to investigate the effect of axle loads, ballast parameters and train velocities on VLL over time. This nonlinear model uses an advanced moving mass loads to represent the vehicles, which travel in loop along perfect track geometry (without any initial track irregularities), as shown in Figure 4.0-4. To perform the designed model, the High-Performance Computing (HPC) facilities have been used through the BlueBEAR platform. It (part of it) consists of two P100 nodes each with 2 x 10 core Boradwell (x86_64) CPUs (central processing units), 1 x NVIDIA Tesla P100, 16GB GPU, 120 GB system memory (BEAR 2023).

In most ballasted railway tracks, it is known that the ballast settlement is the main source of VLL. According to Selig and Waters (1994), there are three necessary conditions for that: (i) existence of filter/separation layer between the coarse ballast and fine subgrade, (ii) a sufficiently strong subgrade or reinforcement of the subgrade/subgrade combination, and (iii) good drainage of water entering from the surface. These conditions have been assumed in this study to model the track.

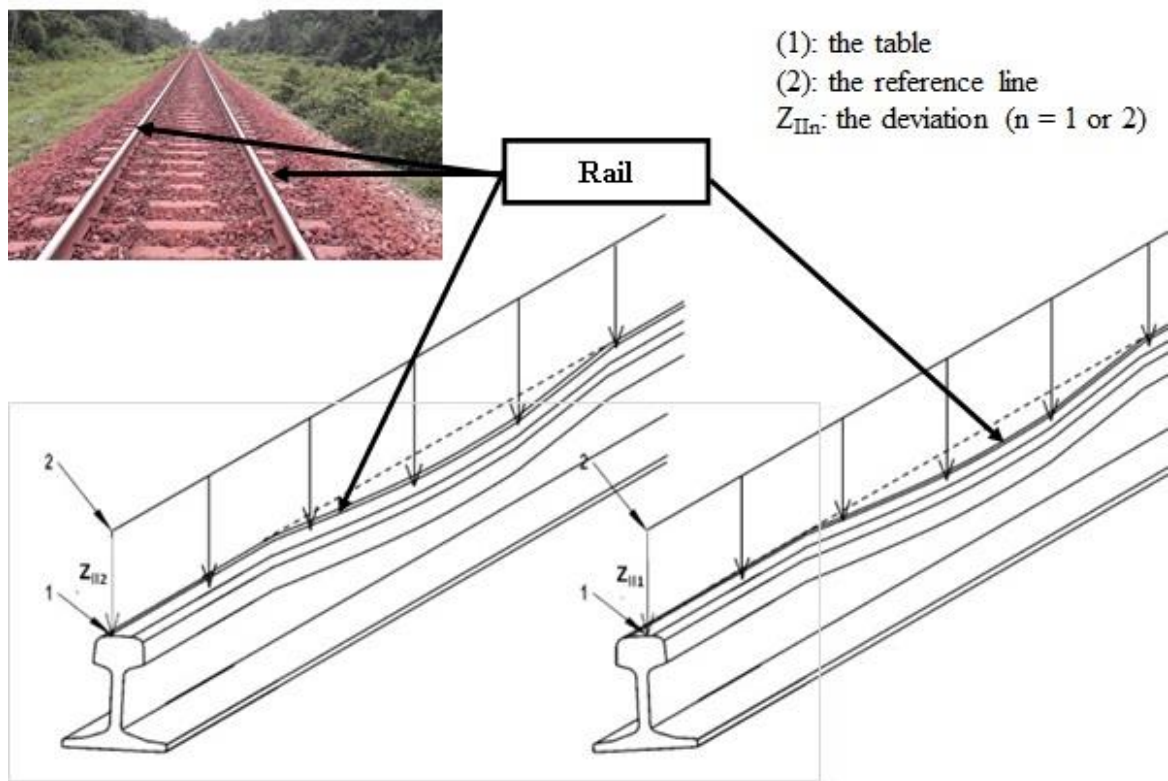
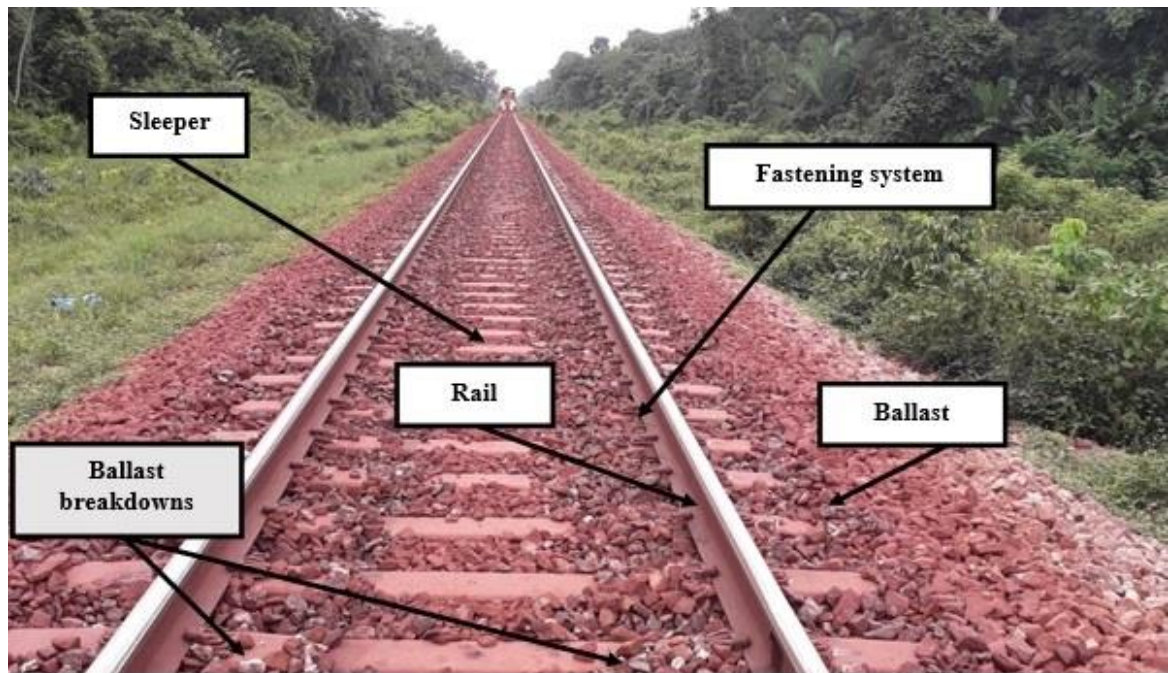


Figure 4.0-2. Typical single ballasted railway track in the EFC and some of its components (top) and track geometric vertical levelling concept (bottom) (adapted from BS-EN-1348-1 2019, and Melo et al. 2022).

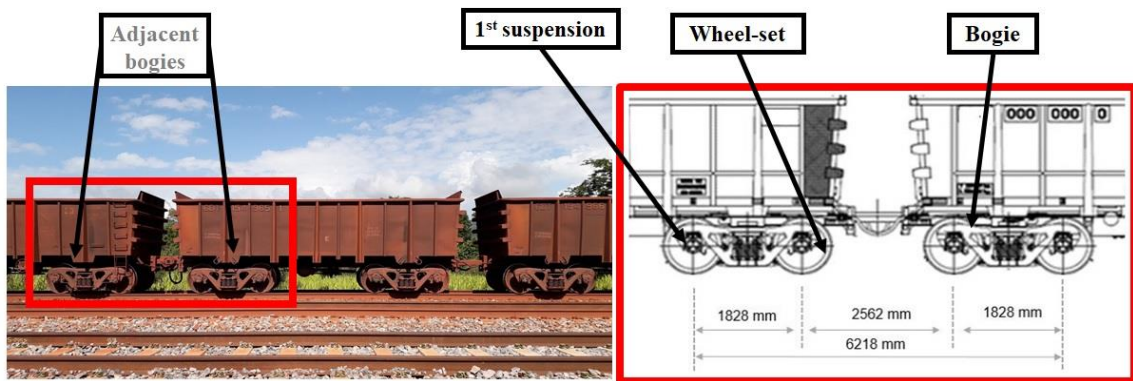


Figure 4.0-3. Typical heavy-haul railway vehicle in the EFC: iron ore wagons (top), and in details (bottom) the vehicle model configuration illustrating the adjacent bogies and its components (adapted from Santos 2015, Costa 2016, Costa et al. 2016, and Melo et al. 2022).

Table 4.0-1. Track and vehicle parameters (modified from Santos 2015, Costa 2016, and Melo et al. 2022).

Track Component (1)	Type	Constitutive Material	Finite Element	Dynamic Parameter(s)
Rail (2)	136RE	Elastic	Beam	Density: $7.85e-9 \text{ ton/mm}^3$ Young's Modulus: $2e5 \text{ N/mm}^2$ Poisson's Ratio: 0.3
Sleeper (3), (4)	Mono-block concrete	Elastic	Beam	Density: $2.5e-9 \text{ ton/mm}^3$ Young's Modulus: $4.3e4 \text{ N/mm}^2$ Poisson's Ratio: 0.15
Fastening System	Fast-clip and rail pad	Elastic	Spring	Elastic Stiffness: $1.7e5 \text{ N/mm}$

Ballast ⁽⁵⁾	Fresh crushed rock	Elastic-plastic	Spring and Damper	Elastic Stiffness: 45.43 MN/mm Yield Force: 250-500 N Tangent Stiffness: 150-500 N/mm Damping constant: 3.2 N/mm
Sub Ballast	A-6 (TRB)	Elastic	Solid	Density: 1.7e-9 ton/mm ³ Young's Modulus: 400 N/mm ² Poisson's Ratio: 0.33
Reinforcement of the Subgrade	NA	Elastic	Solid	Density: 1.5e-9 ton/mm ³ Young's Modulus: 160 N/mm ² Poisson's Ratio: 0.36
Subgrade	NA	Elastic	Spring	Elastic Stiffness: 1 kN/mm
Vehicle Component (6)	Type	Constitutive Material	Finite Element	Dynamic Parameter(s)
Wheel Set	6 ½" X 9", wheel diameter: 965 mm	Rigid	Beam	Density: 7.85e-9 ton/mm ³ Young's Modulus: 2e5 N/mm ² Poisson's Ratio: 0.30
1 st Suspension	NA	Elastic	Spring and Damper	Elastic Stiffness: 1.751e5 N/mm Damping Constant: 3.502 N.s/mm
Bogie	Ride Control	Rigid	Shell	Density: 7.85e-9 ton/mm ³ Young's Modulus: 2e5 N/mm ² Poisson's Ratio: 0.3

Notes:

(1) Track gauge: 1,600 mm; (2) ASTM 136RE rail weight: 68 kg/m; (3) Mono-block concrete sleeper length, height, and width: 2,800 mm, 250 mm, and 265 mm, respectively; (4) Spacing sleepers: 610 mm; (5) Crushed rock ballast height and shoulder: 300 mm and 300 mm, respectively; (6) Key railway vehicle: GDE wagon to transport iron ore.

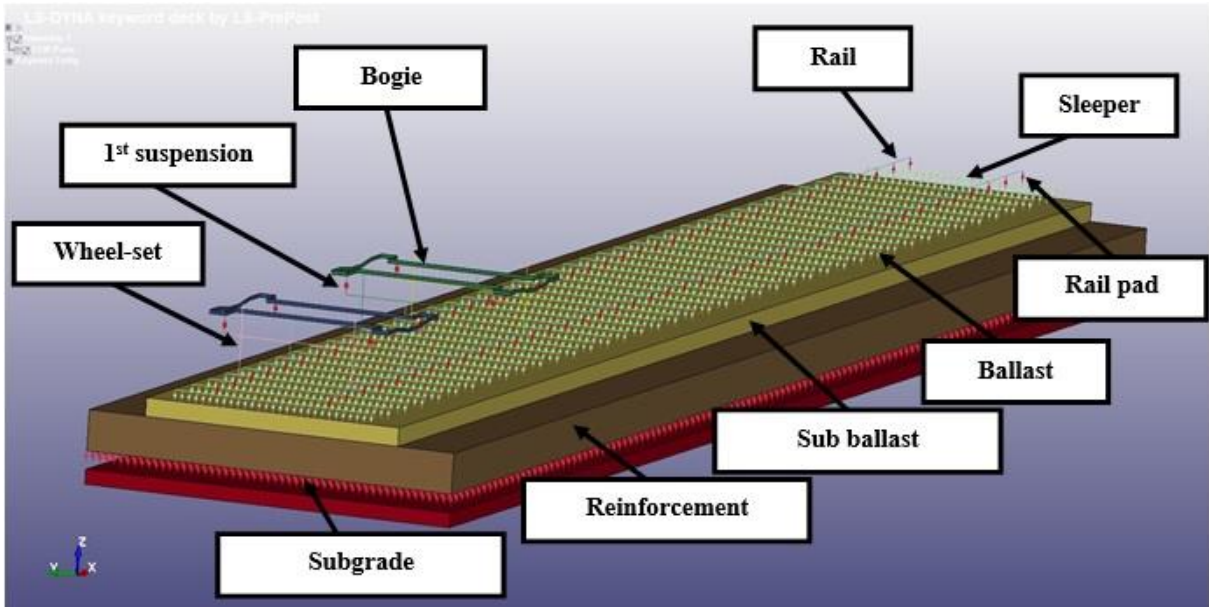


Figure 4.0-4. EFC's railway track and vehicle model on LS-Dyna FE software (adapted from Melo et al. 2022).

Additionally, the ballast is a gravel-size crushed rock that forms the top layer of the railway track structure, in which the sleeper is embedded and supported (Li et al. 2016), and it is subjected to a uniquely severe combination of loading stresses and environmental exposure, under cyclic loadings. As a granular layer, its deformation can be due to particle rearrangement to a denser packing and particle breakage with the smaller particles moving into the voids of the larger particles. This vertical cumulative deformation of the ballast is considered and may be represented on FE model as an elastic-plastic discrete element with isotropic hardening. It has a bilinear force-displacement relationship that is specified by elastic stiffness, a tangent stiffness, and a yield force (LS-Dyna 2018), as illustrated in Figure 4.0-5, and in which the applied load is split into a sequence of increments (cyclic loadings). The force-displacement relation during cyclic loading can be written as (Melo et al. 2022):

$$\hat{f}_n = F_y * \left(1 - \frac{K_t}{K_e}\right) + K_t * \Delta l_n, \quad (4.1)$$

where ‘ n ’ is the number of cycles, ‘ \hat{f}_n ’ is the actual force, ‘ K_e ’ is the elastic stiffness, ‘ K_t ’ is the tangent stiffness, ‘ F_y ’ is the yield force, and ‘ Δl_n ’ is the increment of track settlement.

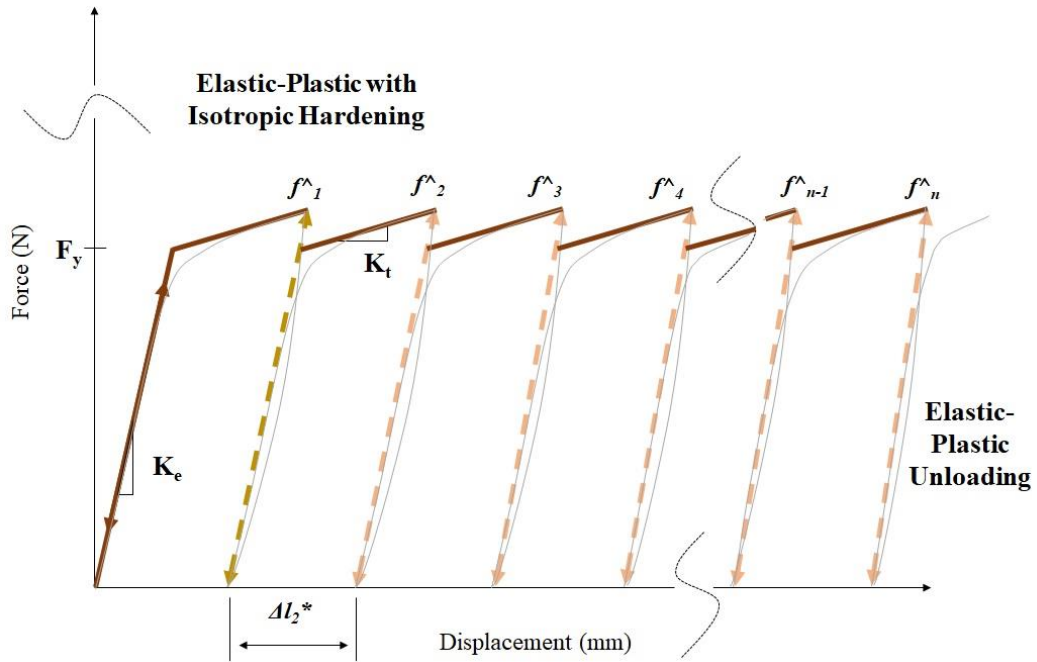


Figure 4.0-5. Loading and unloading force-displacement curves for considering the ballast elastic-plastic behaviour (modified from Melo et al. 2022).

On the other hand, over a period, the ballast voids become progressively filled with not only fine particles (fouled) from the particle breakage, but also, for example, fine particles that fall from iron ore loaded wagons during railway traffic. According to Li et al. (2016), the deterioration of ballast is expected to produce a reduced frictional resistance between the particles than the value of a fresh ballast. Adding this to the modification of ballast state as mentioned before, the ballast track parameters change after several cyclic loadings, however, it is not considered in this modelling.

It is important to highlight that it is difficult to translate the real track conditions to a numerical study. To overcome partially these challenges, a smooth track methodology to develop this study is indicated in Figure 4.0-6. Previously, a wide range of literature had been reviewed regarding track geometry degradation (Melo et al 2020). The research also analyses the collected data from railway companies in Brazil, defines some assumptions and limitations of the study, designs the numerical studies (the railway track and vehicle model), and performs and provides the validation of the model, under different cyclic loadings conditions. Following on from this study, performance, and analysis of the long-term behaviour of the model are presented, dependent variables are identified and final graphics to predict the track geometry VLL, under different parameters, are proposed (Melo et al. 2022).

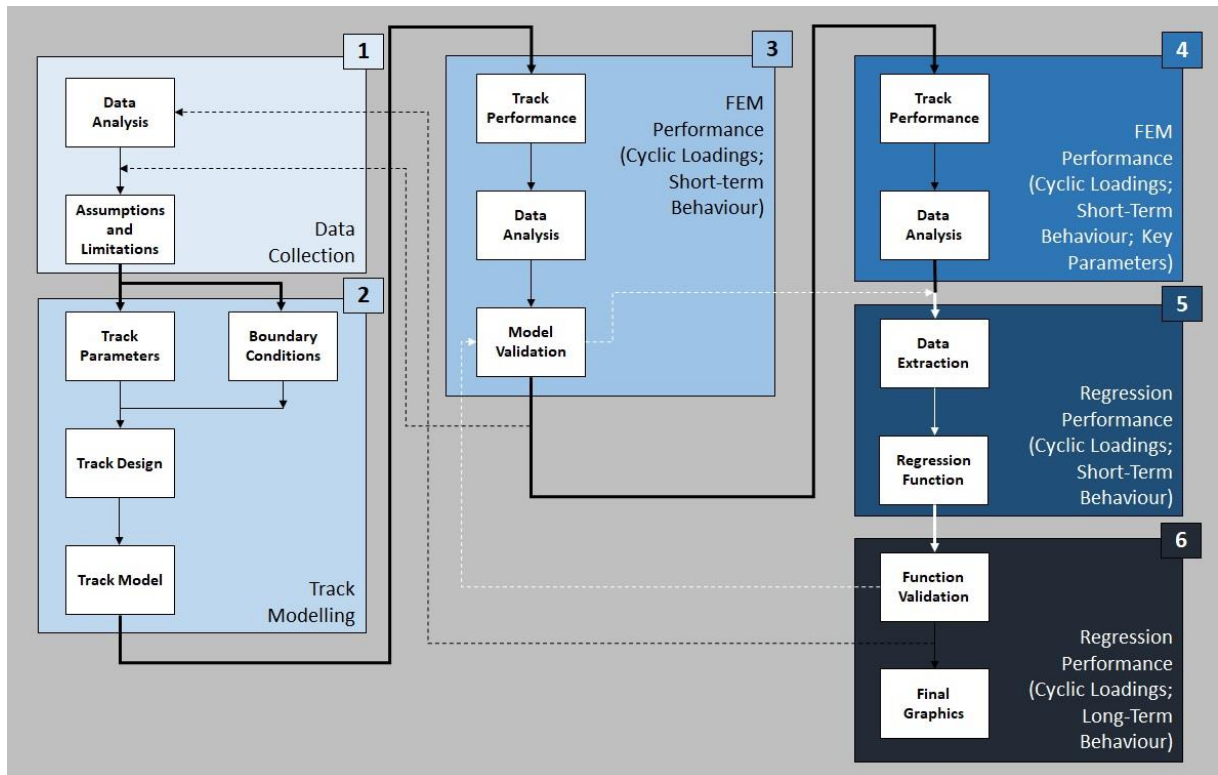


Figure 4.0-6. Smooth track methodology flowchart (modified from Melo et al. 2022).

One of the key challenges to be addressed by this study is associated with the residual (permanent or plastic) ballast settlement which is extremely small (in the order of a nanometer) with each cyclic loading. Another issue to be overcome is related to the computational effort to perform the model. Despite the fast development of computing tools, the numerical solving is affected by computational time limitations. To solve this issue, a mass scaling to increase the time step duration in each cycle (LS-Dyna 2014, and LS-Dyna 2019), and a time scaling computed on a shorter load step in loop are implemented. It is also assumed that the response in a shorter load step is a good representation of the behaviour in real loadings — this is validated by other studies (ORE-D-71 1978, Partington 1979, Hay 1982, Selig and Waters 1994, and Indraratna et al. 2011), and the material properties do not change with the number of load cycles, which is a limitation of this model (Abadi 2016).

Initially, the numerical study is carried out using LS-Dyna and the maximum values of vertical rail displacement (VRD), under cyclic loadings, are numerically generated by the nonlinear FE model. Consecutively, the maximum values of VRD under cyclic loadings (short-term behaviour) are extracted, plotted, and regressed by a Napierian logarithmic function to provide an analytical estimation of the maximum VRD for the cyclic loadings as stated earlier. This equation can be written as (Melo et al. 2022):

$$MaxVRD = a * \ln(N) + b, \quad (4.2)$$

where ‘*MaxVRD*’ is the maximum vertical rail displacement, ‘*a*’ is the rate of ‘*N*’ is the number of cyclic loadings, and ‘*b*’ is the initial rail displacement.

After this initial investigation, the differences between each 4-cycle loads into the long-term behaviour (<6 MGT) of MaxVRD regressed function (Equation 4.2) are calculated. The

results indicate the first term of that regressed function as the track geometry VLL, which also may be written as:

$$VLL = a_{VLL} * \ln(N), \text{ or} \quad (4.3)$$

$$VLL = a_{VLL} * \ln\left(\frac{T}{W}\right), \quad (4.4)$$

where ‘*VLL*’ is the vertical levelling loss, ‘*a_{VLL}*’ the rate of ‘*VLL*’, ‘*N*’ is the number of cyclic loadings, ‘*T*’ is MGT and ‘*W*’ is the axle load (in tonnes).

Equation 2.3 provides an estimation of the cumulative VLL for the real cyclic loadings. Such a result is also compared to the triaxle experiments under repeated loadings carried out by Costa (2016) at the same operational and track conditions as above-mentioned. Additionally, different operational and track characteristics are applied to the verified model and the outcomes are also compared to the studies provided by Indraratna et al. (2012) and Partington (1979). This stage is related to the model validation as indicated in Figure 4.0-6.

After validating the track model under cyclic loadings, the simulations continue being performed – Stage 4 (parametric approach) – varying three key parameters: axle load (15–40 tonnes, light to heavy haul loadings), train velocity (60–160 km/h, low to medium speeds) and ballast tangent stiffness (300–500 N/mm, softer to stiffer ballast plastic deformations). The results are also extracted and analysed and differ to the previous stage – the model validation, not only the rates of VLL are identified but also, they are plotted to evaluate both the behaviour of VLL and the influence of those three different parameters on it. Furthermore, the final graphics explicitly indicate a predictable behaviour of VLL on rail track surface (wheel-rail contact) to those dynamic characteristics, under cyclic loadings.

4.4. Unsupported Sleepers Track Model

In a ballasted railway track, ballast pockets beneath the sleeper can occur due to unequal ballast settlements that may cause a gap between the ballast and the sleeper described as “unsupported sleepers” tracks, as mentioned in Chapter 3. It results that one or more sleepers can be partially unsupported from the rail as some parts of rail remain suspended causing a variation of dynamic force in the track section, which can further escalate and damaging the track components, especially the ballast, affecting the vertical profile and increasing the vertical levelling loss (VLL).

To model the referenced ballasted track, it has been considered that the primary source of VLL is the ballast settlement (Melo et al. 2022), which means that there is a robust set of subgrades (Selig and Waters 1994). Besides, as the ballast is a granular layer subjected to an extreme stress under repeated loadings, its settlement can be caused by particle rearrangement and/or breakage implying necessarily vertical cumulative deformation (Li et al. 2016). According to Melo et al. (2022), this situation can be characterized on FE model by an elastic-plastic discrete element with isotropic hardening, in which the applied load is split into a sequence of accretions (repeated loadings).

Additionally, in an unsupported sleeper (US) track section, the gap is modelled as a non-linear function underpinned by displacements events as indicated in Figure 4.0-7. To guarantee that the sleepers can transfer the load to the ballast properly, the “gap” is defined as a compressive displacement which the discrete element sustains before beginning the force-displacement relation given by the load curve (LS-Dyna 2014, and LS-Dyna 2019). As soon as the sleeper is loaded and moves towards the ballast, a maximum vertical rail displacement (MaxVRD) is achieved. However, it is important to highlight that no force acts on ballast

underneath the sleepers until a predesigned gap is ceased, which reduces the ballast stiffness to a lower level (Zhang et al. 2016).

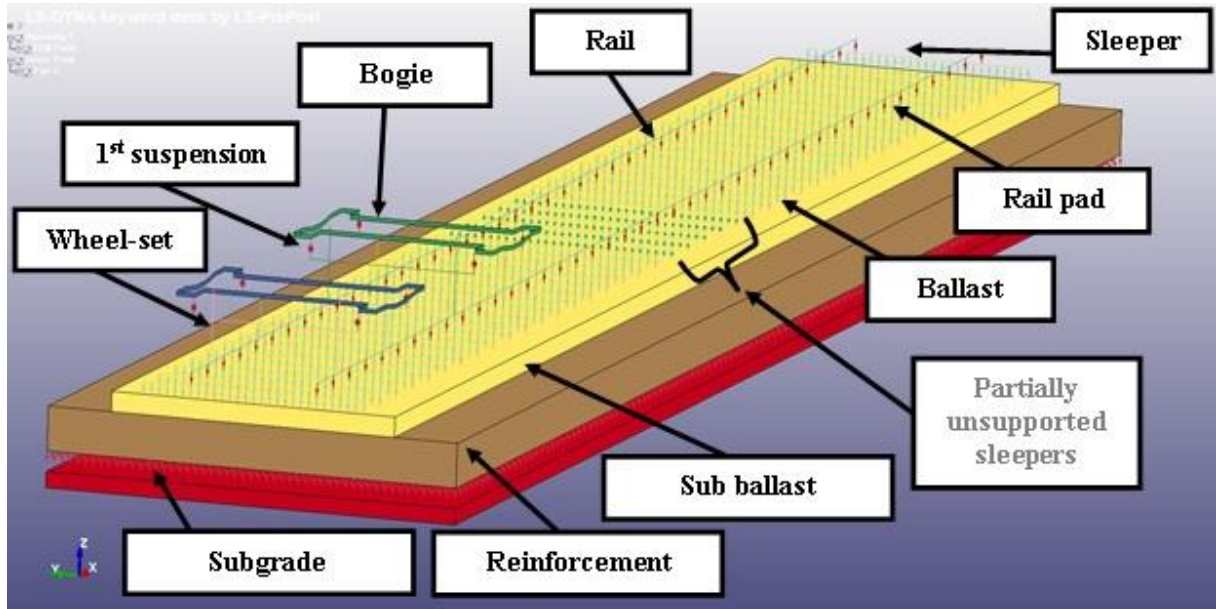


Figure 4.0-7. Railway track and vehicle model on LS-Dyna FE software (in detail, smooth and US track segments) (modified from Melo et al. 2023a).

For modelling the traditional US, the discrete elements beneath the sleepers are eliminated, which means that there is not any transfer load from the sleepers to the ballast directly beneath the sleepers (Zhu et al. 2011, and Young and Li 2003). In this condition, the whole load is transferred from the rail to the adjacent supported sleepers, and consequently to the ballast beneath them. The validation of this model will be presented in Chapter 6. In this study, which focuses on low to medium frequencies and heavy-haul axle loads, the sleeper is modelled as a beam element due its higher computational efficiency and approachable results if compared to a solid element, as pointed out by Lundqvist and Dahlberg (2005), Sysyn et al. (2020), and Xu and Lu (2021). The non-linear characteristics of the model are shown in Figure

4.0-8. The force-displacement relationship during repeated loading can be written as (Melo et al. 2023a):

$$f_n^{\wedge} = \begin{cases} 0, & \text{for Gap} > \text{MaxVRD} \\ F_y * \left(1 - \frac{K_t}{K_e}\right) + K_t * \Delta l_n, & \text{for Gap} \leq \text{MaxVRD} \end{cases} \quad (4.5)$$

where ‘ n ’ is the number of cycles, ‘ f_n^{\wedge} ’ is the actual force, ‘ K_e ’ is the elastic stiffness, ‘ K_t ’ is the tangent stiffness, ‘ F_y ’ is the yield force, and ‘ Δl_n ’ is the increment of track settlement.

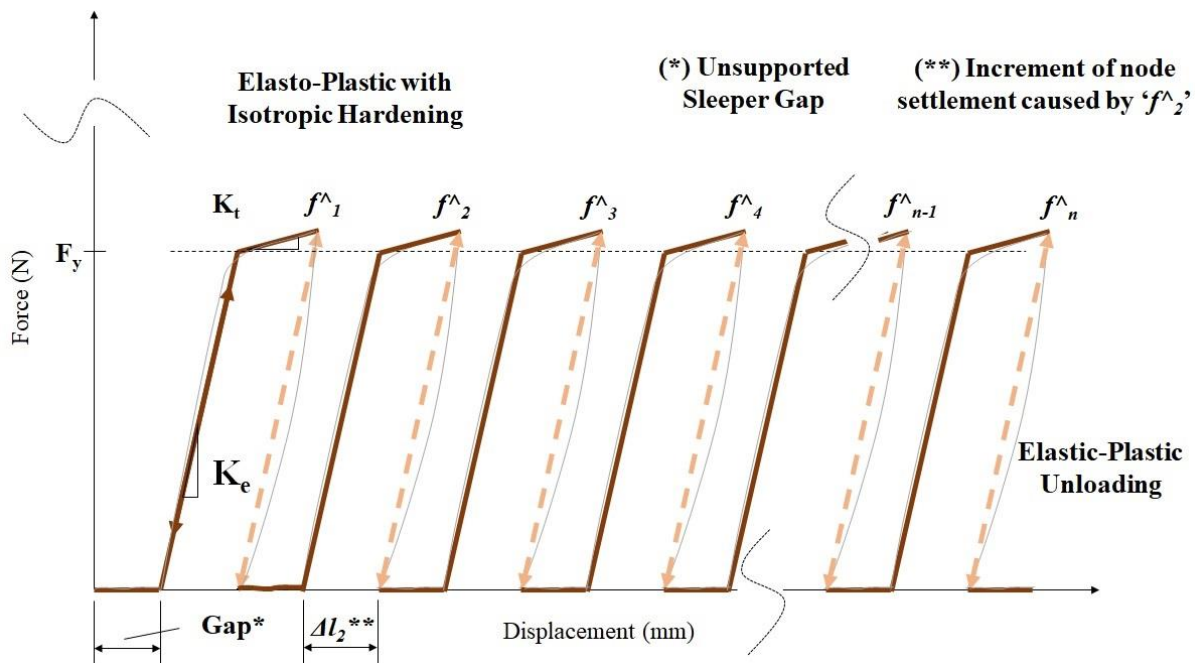


Figure 4.0-8. Loading and unloading force-displacement curves for considering the ballast elastic-plastic behaviour and US (modified from Melo et al. 2023a).

At first, the maximum values of vertical rail displacement (MaxVRD) are numerically generated by the nonlinear FE model under repeated loadings, short-term behaviour, and track

conditions, the later specifically related to the condition of sleeper support. The outcomes of numerical simulation are regressed by a Napierian logarithmic (LN) function to provide an analytical estimation of the MaxVRD for the repeated loadings of the track with supported sleepers as proposed in Section 4.3. Following this initial investigation, the differences between each 4-cycle loads into the long-term performance of the MaxVRD regressed functions for smooth track are determined (Equations 4.2). The outcomes suggest the first term of Equation 2.2 as the track geometrical VLL (Equations 4.3 and 4.4). Equation 4.3 provides an estimation of VLL (smooth track) for the real repeated loadings (Melo et al. 2022).

In turn, the MaxVRD values curve is also numerically generated considering the effect of the US on vertical rail displacement in a short-term behaviour. The ratio difference between the MaxVRD for US and the MaxVRD for smooth track, under the same technical and operational conditions, is also calculated. However, the analytical ratios are initially unstable ($N < 200$ cycles) due the different displacements when the railway vehicles move forward or backward as well as the large initial ballast settlement in response to the gap underneath the sleeper. Therefore, this study proposes to consider the ratio curve from 200 cycles on, designating this as a more stable phase that represents properly the response of US on VLL over time. The ratio curve indicates how much both the number of US and the gap beneath sleepers influence the VLL under cyclic loadings. It can be regressed by a Power function to provide an analytical estimation of the response of US on VLL. This equation can be written as (Melo et al. 2023a):

$$\mu = e_{US} * N^{f_{US}}, \text{ for } 'N' \geq 200, \text{ or} \quad (4.6)$$

$$\mu = e_{US} * \left(\frac{T}{W}\right)^{f_{US}}, \text{ for } '\left(\frac{T}{W}\right)' \geq 200, \quad (4.7)$$

where ‘ μ ’ is the US effect function, ‘ e_{US} ’ the initial effect of US, ‘ f_{US} ’ the rate of ‘ μ ’, ‘ N ’ is the number of repeated loadings, ‘ T ’ is million gross tons (MGT) and ‘ T ’ is the axle load (in tonnes).

To validate the effect of US on VLL (Equation 4.6), the wheel-rail contact force of the model is also compared to the field experiments carried out by Azizi et al. 2020, Azizi et al. 2021a, and Azizi et al. 2021b, at the similar set-up considering traditional US. This stage is related to the model validation and will be presented in Chapter 6. Examining that the US can affect the VLL over time, it is possible to improve Equation 4.3 multiplying it by ‘(1 + Equation 4.6)’. Thus, the new VLL (nVLL) can consider the effect of US. It may be written as (Melo et al. 2023a):

$$nVLL = [1 + e_{US} * (N)^{f_{US}}] * a_{VLL} * \ln(N), \text{ for } 'N' \geq 200, \text{ or} \quad (4.8)$$

$$nVLL = \left[1 + e_{US} * \left(\frac{T}{W}\right)^{f_{US}}\right] * a_{VLL} * \ln\left(\frac{T}{W}\right), \text{ for } \left(\frac{T}{W}\right) \geq 200, \quad (4.9)$$

where ‘ $nVLL$ ’ is the new ‘VLL’ (considering the effect of US), ‘ a_{VLL} ’ the rate of ‘VLL’ (smooth track), ‘ e_{US} ’ the initial effect of US, ‘ f_{US} ’ the rate of ‘ μ ’, ‘ N ’ is the number of repeated loadings, ‘ T ’ is million gross tons (MGT) and ‘ W ’ is the axle load (in tonnes).

From the previous stages, this study continues to carry out numerical simulations varying three parameters: number of US (1-5 sleepers), gap beneath sleepers (1-5 mm), and axle load (20, 30 and 40 tons). Train velocity and other track and vehicles parameters are kept constant. Additionally, the dependent variables are identified and the final graphics to predict the effect of US on the track geometrical VLL are proposed. Furthermore, the performance and

the analysis of the long-term behaviour of the model are presented. The methodology to develop this research is indicated in Figure 4.0-9.

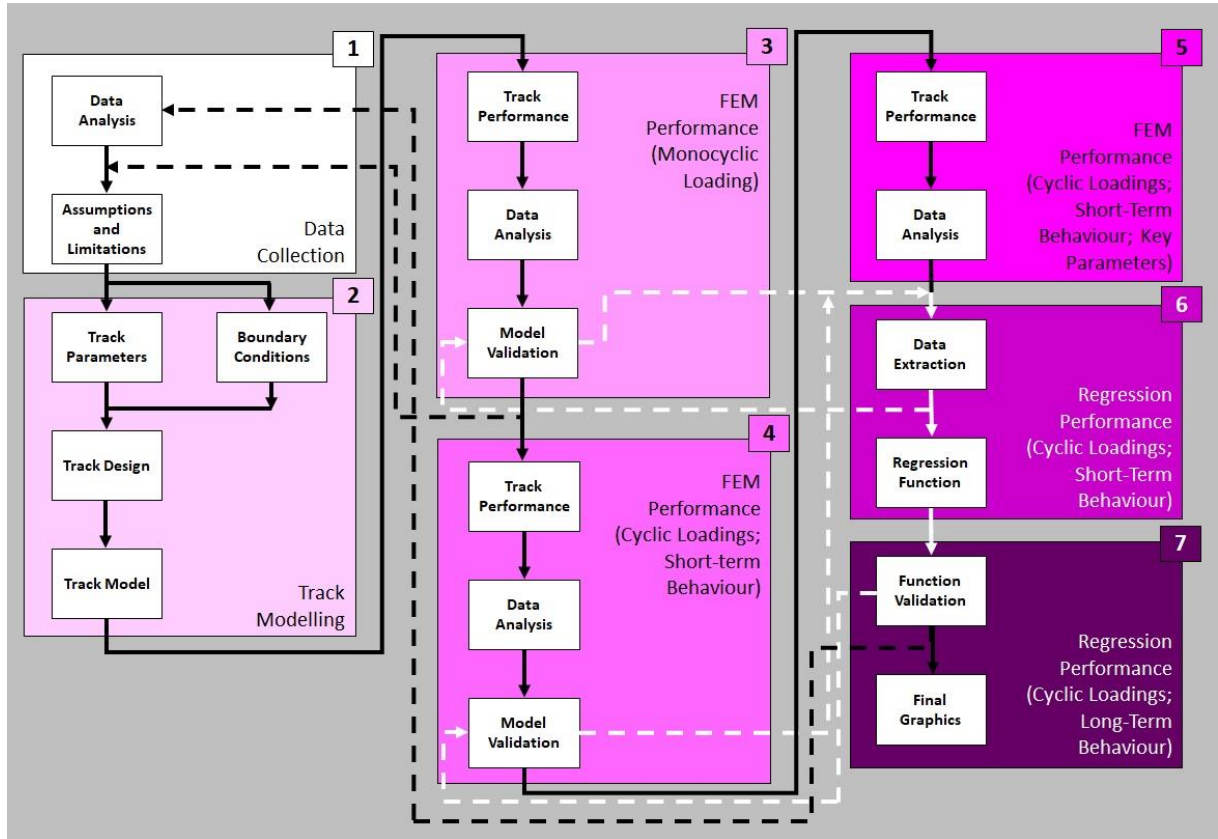


Figure 4.0-9. US track methodology flowchart (modified from Melo et al. 2023a).

4.5. Uneven Track Model

The concept of an uneven track is wide, however, in this research an uneven track is defined as a track in which the initial track irregularities post-construction or maintenance activity are assessed by a recording car (RC) vehicle to provide a more appropriated “picture” of the track condition. On the contrary of a smooth track, an uneven track considers the existence of track geometric irregularities (even small ones), which permits any track-vehicle system model to capture the dynamics forces caused them. These forces due to initial track irregularities (ITI)

are responsible for expanding the vertical levelling loss (VLL) under dynamic cyclic loadings, due to compaction of railway ballast, as mentioned before.

Based on a typical heavy-haul ballasted railway track as illustrated in Figure 4.0-10 and its parameters described on Table 4.0-1, a 25-meter straight track segment and two adjacent bogies of a typical wagon (the greatest load solicitation) have also been modelled in 3D on LS-Dyna (Melo et al. 2022).

The track-vehicle model is simulated by applying both linear elastic and elastic-plastic constitutive law of the materials to investigate the effect of initial track irregularity (ITI) on the VLL under cyclic loadings. This nonlinear model employs moving mass loads to represent the vehicles, which travel in loop along both smooth tracks (perfect track geometry) and uneven tracks, the last ones with two different sets of ITI.

The objective of the models is to determine the effects of ITI on track geometrical VLL over time. To simulate the designed model, the BlueBEAR platform (BB) – a powerful and fast computing facility – has been used to accelerate performance. Figure 4.0-10 shows the railway track and vehicle model on LS-Dyna FE software (in detail, smooth track and left and right vertical rail irregularities).

Considering that the railway ballast settlement is the principal source of VLL (Melo et al. 2022), the track subgrade components are modelled with high elastic resilience modulus (Young's modulus) including the reinforcement of subgrade (Nguyen et al. 2016). Also, as the ballast is a granular layer subjected to an extreme stress under cyclic loadings, its accumulative deformation can be caused by compaction and breakage implying undoubtedly vertical settlements (Li et al. 2016). This situation can be characterized by FE models using an elastic-plastic discrete element with isotropic hardening, in which the applied load is split into a sequence of increments (cyclic loadings), as aforementioned. Additionally, in a straight track

section, the ITI (or initial roughness) is modelled innovatively as a non-linear function underpinned by displacements events and by a load curve of a given vertical profile deviation (in mm) of the rail top from the theoretical centerline (smooth track) of the beam elements as a function of distance along the track from the origin node of the rail above of each concrete sleeper (LS-Dyna 2014).

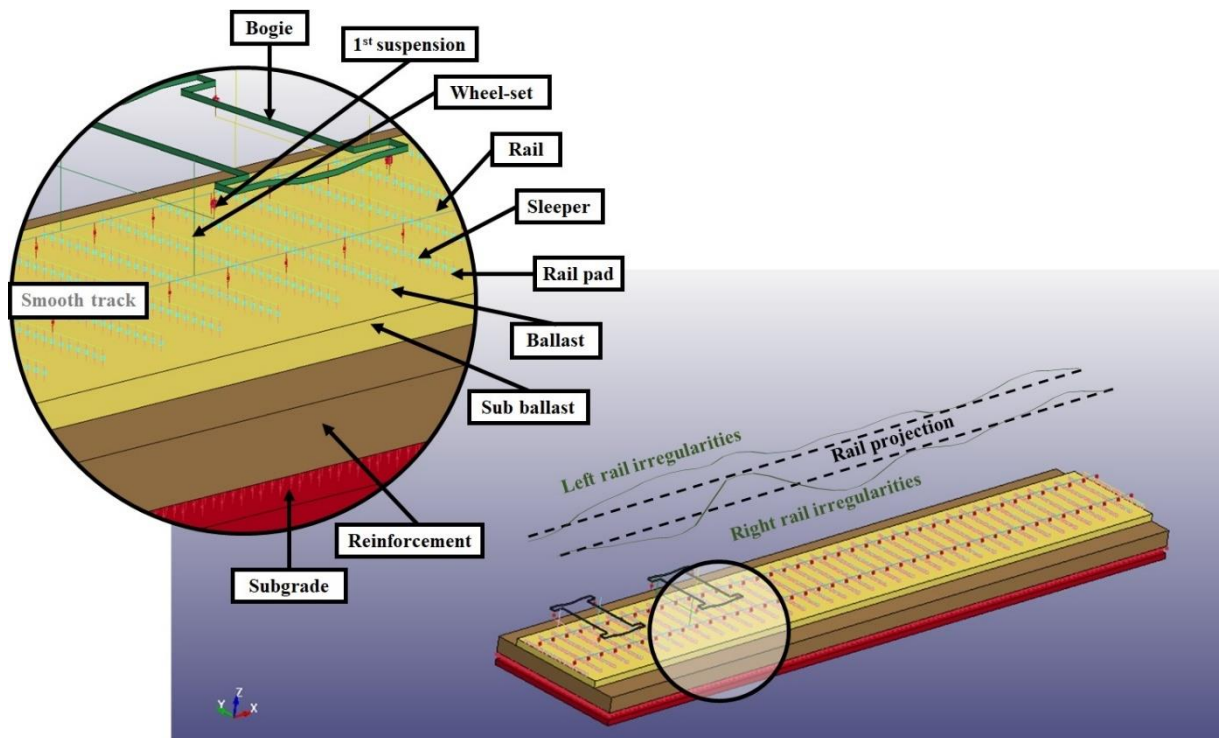


Figure 4.0-10. Railway track and vehicle model on LS-Dyna FE software (in detail, smooth track and left and right vertical rail irregularities) (Melo et al. 2023b).

The ITI curve profiles are measured from both rails of the same segment of track so that the relationship between bump and roll modes is correctly captured (LS-dyna 2019). This robust approach can provide new findings related to actual dynamic forces on a ballasted railway track and better understandings from the previous studies about the effect of ITI on VLL over time. As soon as the sleeper is loaded and moves towards the ballast, a maximum vertical rail

displacement (MaxVRD) is achieved (Melo et al. 2022) taking into consideration the effect of vertical profile (Melo et al. 2023b). The validation of this model will be presented in Chapter 7. In this investigation, which focuses on low to medium frequencies and heavy-haul axle loads, the sleeper is also modelled as a beam element due its higher computational efficiency and approachable results if compared to a solid element, as pointed out by Xu and Lu (2021). The non-linear characteristics of the model in each node are shown in Figure 4.0-5. The force-displacement relationship during cyclic loading can also be written as Equation 4.1.

Analogous to Section 4.3, the maximum values of vertical rail displacement (MaxVRD) for each node are generated numerically by the nonlinear FE model under repeated loadings; firstly, on a smooth track, afterward, on an uneven track. The outcomes of numerical simulation are later regressed by a Nepierian logarithmic (LN) function to provide an analytical estimation of the ‘*MaxVRD*’ for the cyclic loadings of a smooth track (without track irregularities) as proposed by Melo et al. (2022). This equation may be written as Equation 4.2 (Melo et al. 2023b).

Following this initial investigation, the differences between each 4-cycle loads into the short-term performance of the MaxVRD regressed function (Equation 4.2) for smooth track are determined. The outcomes suggest the first term of Equation 4.2 as the track geometrical VLL, which also can be written as Equations 4.3 and 4.4 (Melo et al. 2023b).

Equations 4.3 provides an estimation of VLL for the real cyclic loadings in a smooth track (Melo et al. 2022). In sequence, the MaxVRD values curve is also numerically generated considering the effect of two ITI on vertical rail displacement in a short-term behaviour. Therefore, this study originally proposes to compare the response differences between low and medium SD of ITI over time on VLL in a ballasted railway track. The ratio curve indicates how much SD of ITI influences the VLL under repeated loadings (Melo et al. 2023b).

To rigorously validate the effects of ITI on VLL, the wheel-rail contact force of the model as critical and usual parameter of assessment applied worldwide is also compared to the experiments carried out by Gadhav and Vyas (2022) at the similar conditions, including 10-tons axle load and 72-km/h train velocity. This condition has been adopted for the model validation. The validation has been conducted using both time series and power spectral density (PSD) functions to create wavelength-based vertical rail irregularities that are identical to both studies defining in ERRI-B176 as (ERRI-B176 1993, Gadhav and Vyas 2022, and Melo et al. 2023b):

$$S(\omega) = \frac{b_0}{a_0 + a_2 * \omega^2 + a_4 * \omega^4}, \quad (4.10)$$

where wavelengths of range 0.4 m^{-1} to 0.03 m^{-1} with 300 frequency components equidistant from one another are used for creating roughness in left and right rail (Gadhav and Vyas 2022) in 25-m railway track of this investigation (Figure 4.0-11).

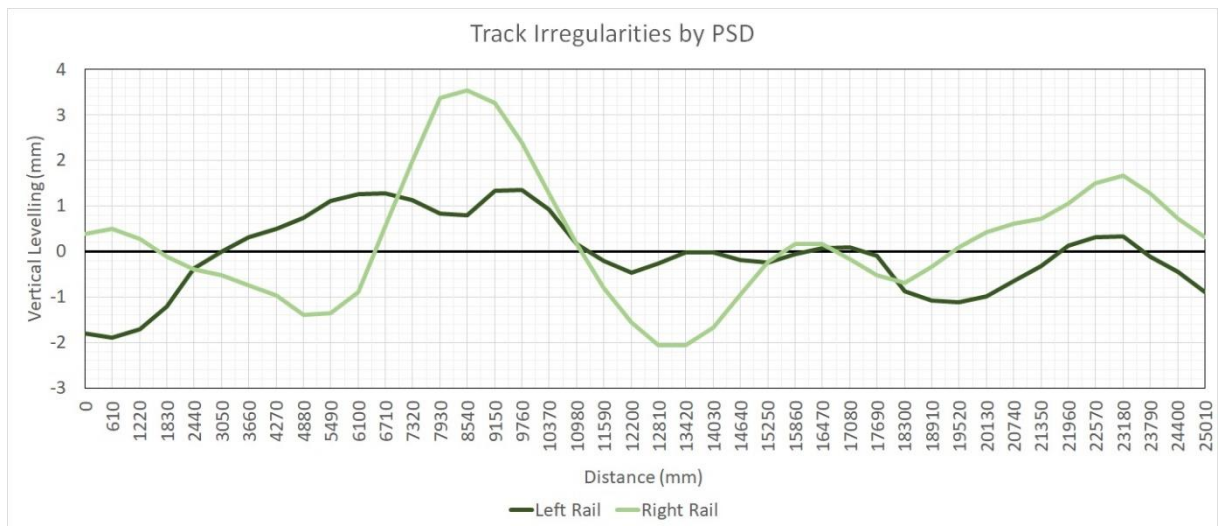


Figure 4.0-11. Vertical profile irregularities created by PSD (Power Spectral Density) in 25-m railway track (modified from Melo et al. 2023b).

Examining that the ITI can affect the VLL over time, it is possible to assume that Equation 4.2 also represents the new VLL (VLL') taking into consideration the effect of ITI. It may be written as (modified from Melo et al. 2023b):

$$VLL' = a_{VLL'} * \ln(N), \text{ or} \quad (4.11)$$

$$VLL' = a_{VLL'} * \ln\left(\frac{T}{W}\right), \quad (4.12)$$

where ' VLL' ' is the new ' VLL ' (considering the effect of ITI), ' $a_{VLL'}$ ' the rate of ' VLL' ' (uneven track), ' N ' is the number of repeated loadings, ' T ' is million gross tons (MGT) and ' W ' is the axle load (in tonnes).

From the validation steps, this study also presents the performance of numerical simulations considering three different parameters: ITI (low and medium SD (Standard Deviation) of ITI registered by railway company recording car – RC, calculated as 0.48 mm and 3.23 mm, respectively), train velocity (60, 70 and 80 km/h), and axle load (20, 30 and 40 tons); other track, vehicle, and operational parameters are kept constant. The rates of SD of vertical profiles are identified and the performance and analysis of long-term behaviour of the model are presented. The methodology to develop this investigation is indicated in Figure 4.0-12.

4.6. Summary

This chapter proposes a general research methodology to investigate the ballasted railway track geometrical degradation under cyclic loadings and elastic-plastic behaviour of material (ballast) filling the current knowledge gaps of considering the global train-track dynamics. It focuses on vertical levelling (VL) track geometric element as it represents more than 50% of track geometric issues in a ballasted railway track.

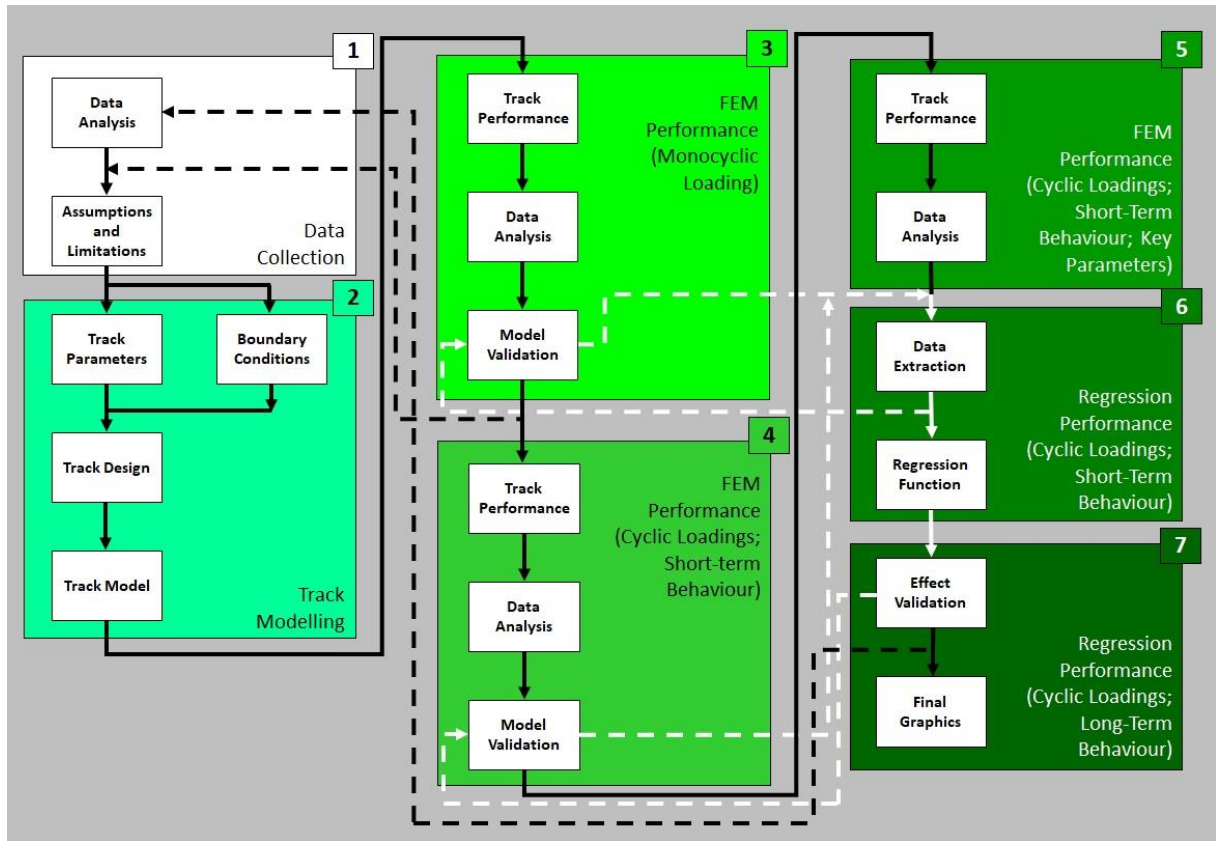


Figure 4.0-12. Uneven track methodology flowchart (modified from Melo et al. 2023b).

Also, it proposes innovative and complementary numerical-analytical methodologies to predict vertical levelling loss (VLL) over different key railway track conditions: smooth track, unsupported sleepers track, and uneven track. The plastic deformation and nonlinearity of material properties, the effect of initial track geometric irregularity effect, and the contacting surfaces, under cyclic loadings, are some of the issues that the methodology proposes to address. It is important to note that other issues are not properly addressed yet such as those also related to railway ballast in which, over a period, its voids become progressively filled with fine particles that fall from iron ore loaded wagons during railway traffic reducing the frictional resistance between the particles if compared to the value of a fresh ballast. Moreover, a reasonable physical understanding about the effects of unsupported sleepers (US) and initial

track irregularities (ITI) on VLL are presented as of great interest for supporting the prediction of the long-term track geometrical degradation as will also be demonstrated in the next chapters. The following chapter will present and discuss the outcomes of the proposed numerical-analytical approach in smooth track (track without geometric irregularities).

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VERTICAL LEVELLING LOSS IN SMOOTH TRACKS

This chapter presents the results and discussion of the application of an innovative numerical-analytical approach to predict ballasted railway track geometrical degradation focused on vertical levelling track geometric element in a smooth track. It briefly presents the topic under investigation and discusses the results obtained from numerical simulation and regression performance of VLL in a heavy-haul railway in Brazil. To verify whether the numerical model can be reliable for predicting the VLL, the validation of the model is also investigated. Moreover, this chapter promotes a parametric approach to extend the study of the effect of different railway dynamic conditions on VLL.

5.1. Introduction

From the previous chapters, a ballasted railway smooth track is known as a track without any initial track geometric defects, or in other words, it is a perfect railway track. In this hypothetical situation, as there is not any track irregularity, the dynamic forces on wheel-rail contact are limited to track, vehicle, and operational condition. This kind of track is mostly used to investigate the behaviour of different track components.

From the literature review in Chapter 3, innumerable VLL predictive approaches have been derived empirically from laboratory and field experiments mostly focusing on ballast settlement. It can be noted that those VLL investigations are presented without any consensus among the experimental conditions and the results meaning that there is a research gap related to how harmonize the VLL predictions. Furthermore, those methods indicate a dependency exclusively on the number of cycles without considering any different operational,

environmental, vehicle, and track conditions. To address those two research gaps, Melo et al. (2022) propose the development of a new hybrid numerical-analytical method considering railway dynamic conditions as described in Chapter 4 e analysed in this chapter.

5.2. Numerical Simulation

Initially, the track model under 368 cyclic loadings (approximately 100s of a shorter loading step in loop) and operational parameters of 20-tonnes axle load and 70-km/h train velocity is performed on HPC. Figure 5.0-1 depicts the VRDs after being extracted and plotted in a time-domain graphic.

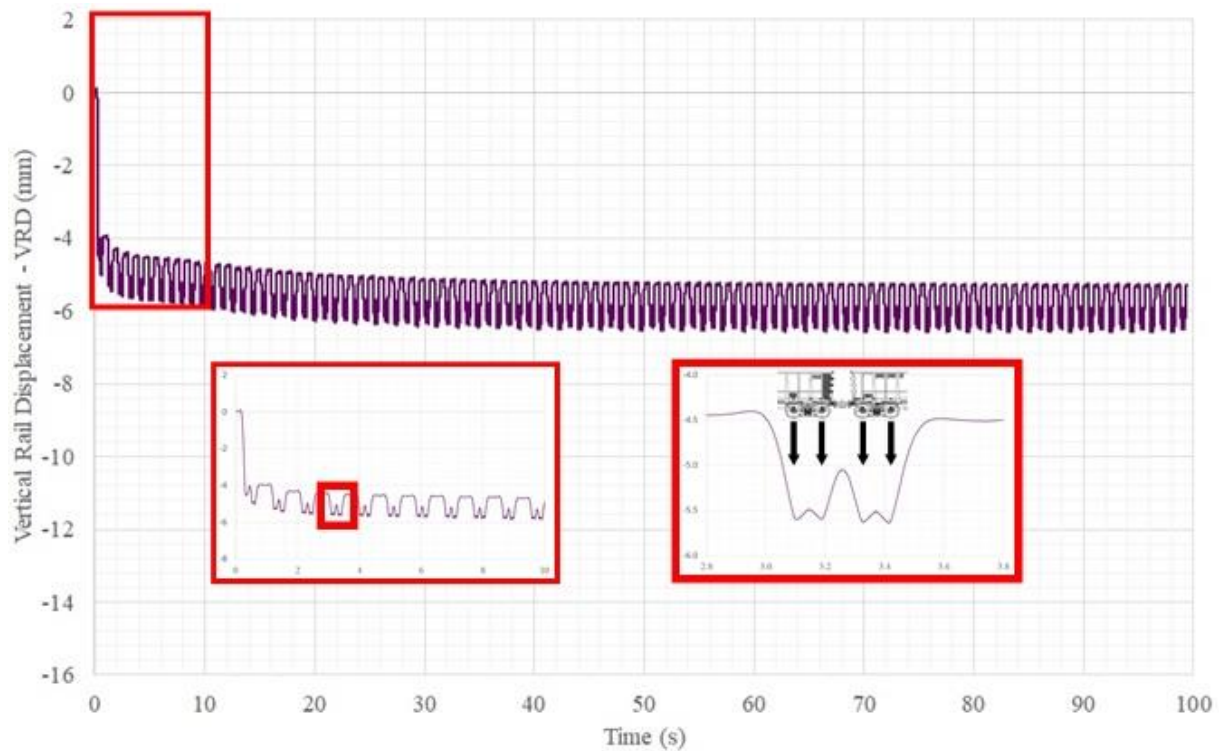


Figure 5.0-1. Vertical rail displacements (VRDs) on FEM (Finite Element Method) under 20-tonnes axle load, 70-km/h train velocity, and 500-N/mm ballast tangent stiffness (in details, left: the initial VRDs, and right: the effect of superposition caused by the wheel loads).

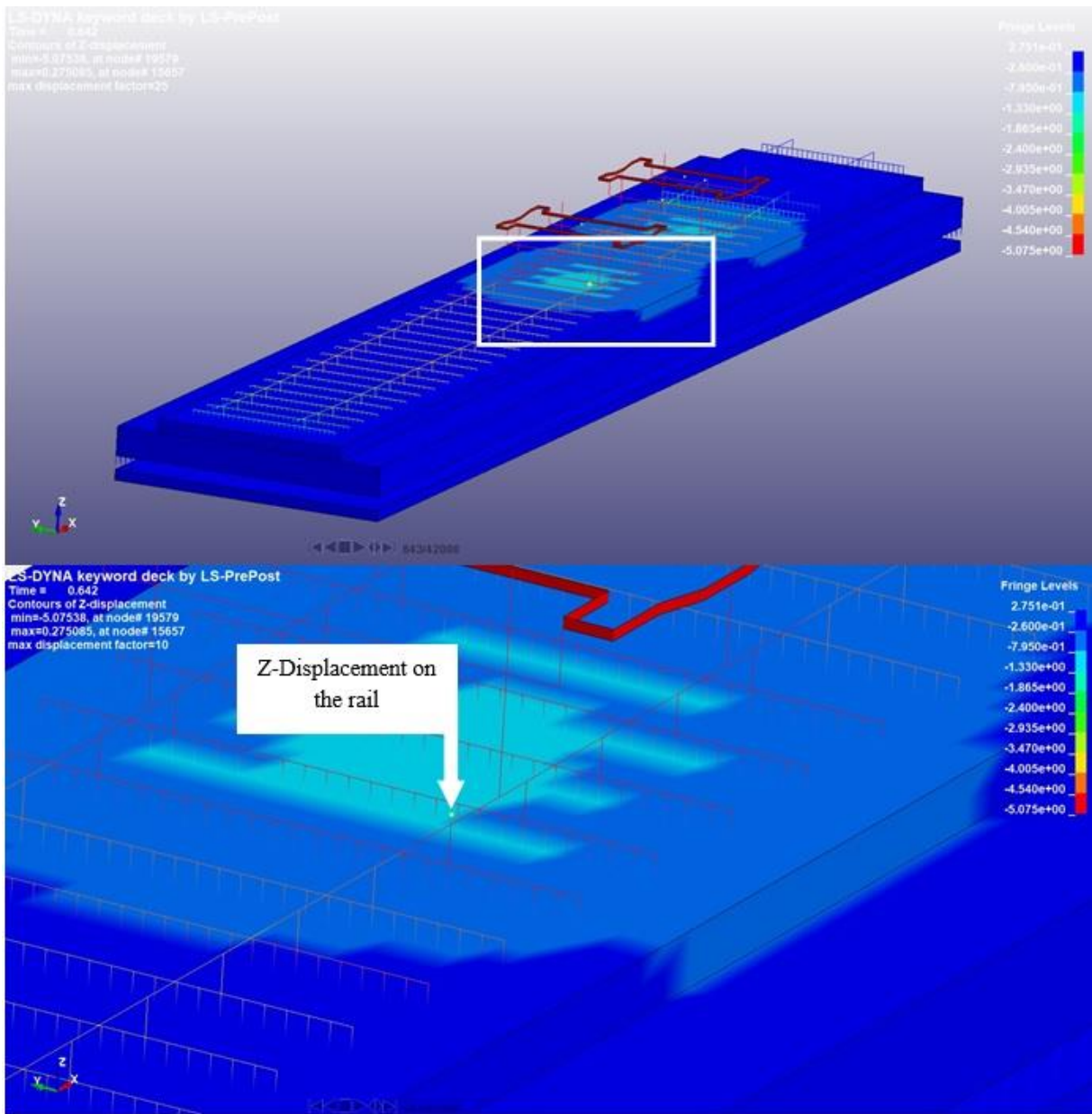


Figure 5.0-2. The track model performed under 20-tonnes axle load, 70-km/h train velocity, and 500-N/mm ballast tangent stiffness (in details – bottom, the rail FE node displacement just after the fourth load cycle).

The VRDs are computed by the summation of elastic-plastic displacement between the wheel and the rail in vertical direction (“Z-Displacement” in Figure 5.0-2) for each load applied.

It is well known that the largest VRDs occur during the first cyclic loadings and correspond to the process in which the gaps between ballast particles are unified and consolidated (Sato 1995). This initial ballast consolidation is considered to depend on both the work done on it (i.e., the axle load and, consequently, the contact force between the track components) and the ballast parameters, particularly the ballast tangent stiffness. A similar trend of VRDs can be found in Figure 5.0-1, in which the slope of those displacements is likely to represent how faster and deeper the railway track loses its vertical levelling. The maximum VRD (MaxVRD) immediately after each four cycles (a half loop) of those cyclic loadings is identified and plotted in a "Number-of-Cyclic-Loadings (un) X VRD (mm)" graphic to support the next step of this analysis. Figure 5.0-3 illustrates the MaxVRD values under 20-tonnes axle load, 70-km/h train velocity and 500-N/mm ballast tangent stiffness.

Napierian logarithmic (LN) function to provide an estimation of the maximum VRD for cyclic loadings as stated before. The coefficient of determination, denoted R^2 , of LN expression, under 20-tonnes axle load, 70-km/h train velocity and 500-N/mm ballast tangent stiffness is 0.9640, indicating reasonably that the FEM results can be replicated by the nonlinear model to the prediction of future outcomes. The results for this step are shown in Figure 5.0-4 where there are two different coefficients: a_{VRD} and b_{VRD} . For the LN function, over 4+ cyclic loadings, the first coefficient (a_{VRD}) indicates in which rate the VRD rises when increases axle load, whilst the second one (b_{VRD}) is related to the initial VRD, both intrinsically related to the 20-tonnes axle load. The results for a_{VRD} and b_{VRD} are 0.3489 mm and 4.6142 mm, respectively, and can be written, based on Equation 4.2, as follows (Melo et al. 2022):

$$MaxVRD \left(20 \text{ tonnes}, 70 \frac{km}{h}, 500 \frac{N}{mm} \right) = 0.3489 * \ln(N) + 4.6142, \quad (5.1)$$

where “ $MaxVRD \left(20 \text{ tonnes}, 70 \frac{km}{h}, 500 \frac{N}{mm} \right)$ ” is the maximum vertical rail displacement under 20-tonnes axle load, 70-km/h train velocity and 500-N/mm ballast tangent stiffness, and “ N ” is the number of cyclic loadings.

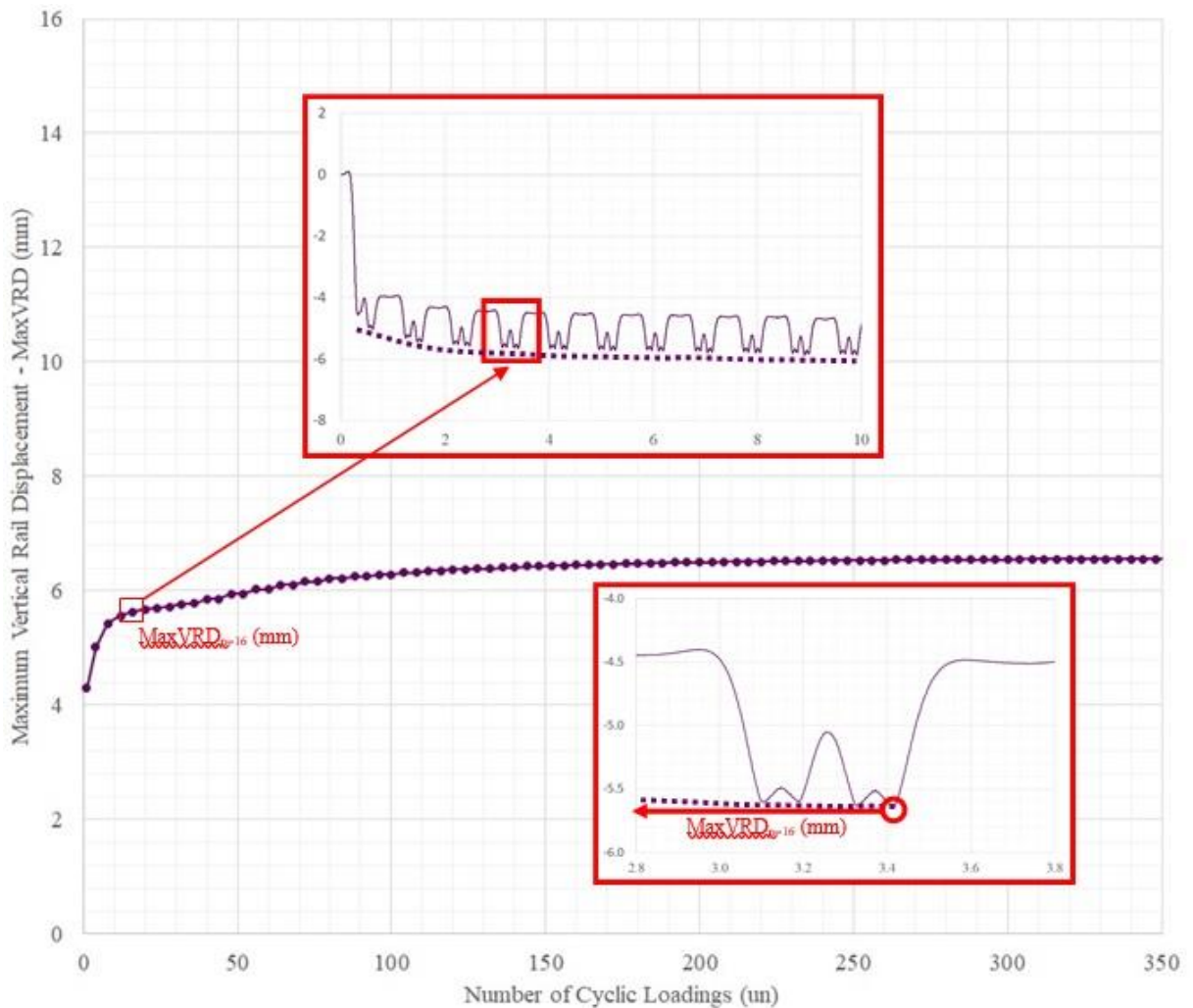


Figure 5.0-3. Maximum vertical rail displacements (MaxVRDs) after each 4-cyclic loading (a half loop) on FEM under 20-tonnes axle load, 70-km/h train velocity and 500-N/mm ballast tangent stiffness (in details, top: the VRDs, and bottom: the MaxVRD after the 16th load cycle).

5.3. Regression Performance

Upon initial investigation, the outcomes of the FEM analysis in the previous section (numerical analysis) are collected to be input into a regression performance. During this stage, the maximum values of VRD (Figure 5.0-3), under cyclic loadings (short-term), are regressed by a

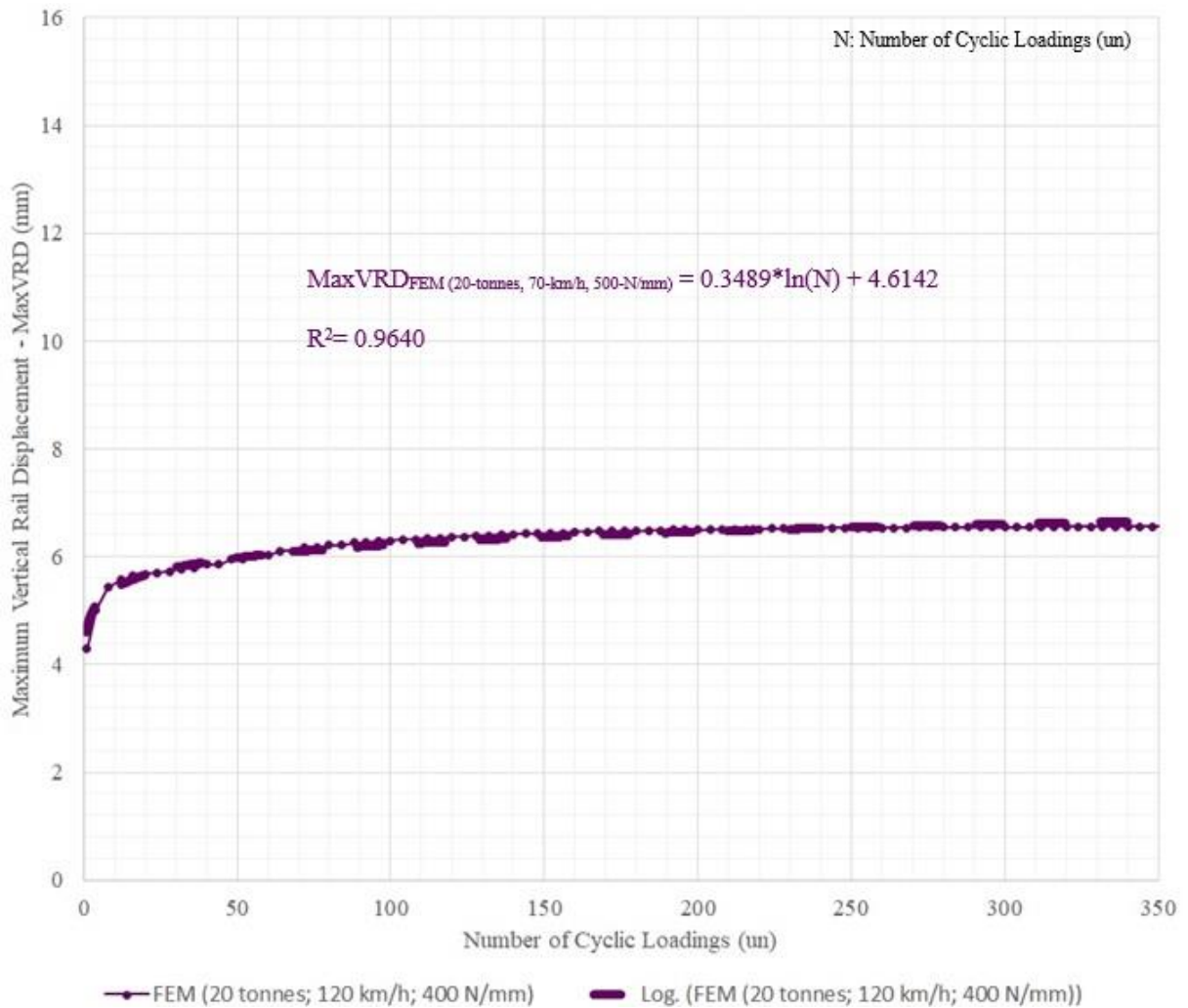


Figure 5.0-4. Regression performance in the short-term behaviour of MaxVRDs after each 4-cyclic loading (a half loop) on FEM under 20-tonnes axle load, 70-km/h train velocity and 500-N/mm ballast tangent stiffness.

Following on the proposed methodology, the differences between each 4-cycle loads for a long-term behaviour (initially, < 6 million gross tonnes or 300 thousand cycle loads) of

the MaxVRD LN function are calculated. The result indicates the first term of that regressed expression (Equation 5.1) as the VLL of track geometry. Therefore, the track geometry VLL for those railway operation and track conditions can be, underpinned by Equations 4.3 and 4.4, written as (Melo et al. 2022):

$$VLL\left(20 \text{ tonnes}, 70 \frac{\text{km}}{\text{h}}, 500 \frac{\text{N}}{\text{mm}}\right) = 0.3489 * \ln(N), \quad (5.2)$$

$$VLL\left(20 \text{ tonnes}, 70 \frac{\text{km}}{\text{h}}, 500 \frac{\text{N}}{\text{mm}}\right) = 0.3489 * \ln\left(\frac{T}{20}\right), \quad (5.2)$$

where “ $VLL\left(20 \text{ tonnes}, 70 \frac{\text{km}}{\text{h}}, 500 \frac{\text{N}}{\text{mm}}\right)$ ” is the vertical levelling loss (in mm) under 20-tonnes axle load, 70-km/h train velocity and 500-N/mm ballast tangent stiffness, “ N ” is the number of cyclic loadings, and “ T ” is the million gross tonnes (MGT).

5.4. Validation of the Model

To examine whether the numerical model can provide reliable insight into the VLL, first the validity of the FEM outcomes regarding the VRD in short-term cyclic loadings must be investigated. Equation 5.2 from previous section (regression performance) provides an estimation of the cumulative VLL for the real cyclic loadings. That result is compared to a robust triaxle experiment (Merheb 2014) under repeated loadings carried out by Costa (2016) under similar operational and track characteristics (20-tonnes axle load, 70-km/h train velocity, and 500-N/mm ballast tangent stiffness – well-compacted crushed ballast) as aforementioned. In Costa’s experiment, the tests are conducted at a train operating between 60-km/h and 70-km/h train velocities. The axle load is 20 tonnes (Costa 2016).

Figure 5.0-5 shows the comparison of VLLs (Vertical Levelling Loss) provided by the numerical (FEM and regression analytics) and the laboratory studies. The numerical-analytical model gives a reasonable match with the measured data in the triaxle test, particularly after 50

thousand cycles. The VLL for 300 thousand cyclic loadings is approximately 4.5 mm on both methods. According to the benchmark models (Dahlberg 2001, and Grossoni et al. 2019), it also implies that the VLL in this study matches very well and falls within the well-compacted ballast track models (1–5 mm for 300 thousand cycles).

Additionally, different operational and track characteristics are applied to the verified model and the outcomes are compared to the studies provided by both Indraratna et al. (2012) and Partington (1979) considering similar conditions, respectively.

In Partington's study, rail have 54 kg/m, and their modulus of elastic and Poisson's ratio are, respectively, 210 GPa and 0.3. The sleepers are installed at 600 mm centres. The rails are fastened by elastic fastenings (e-clips). Wheel has a diameter of 0.81 m. The train run over tracks at 162 km/h. On the other hand, in Indraratna's research, the tests are conducted at a train operating in the proximity of 80-km/h train velocity. The axle loads vary from 25-30 tonnes.

Figure 5.0-6 depicts the comparisons of VLLs of our numerical study to those studies. It is noted that the FE model under 20-tonnes axle load, 120-km/h train velocity and 400-N/mm ballast tangent stiffness – medium-compacted crushed ballast – copes well with the Partington's investigation after 150 thousand cycles. Different to the previous comparisons, the FE model under 30-tonnes axle load, 80-km/h train velocity and 350-N/mm ballast tangent stiffness (softer-compacted crushed ballast) conforms well to Indraratna's study (Indraratna et al. 2012) even on the initial number of load cycles. The VLLs for 300 thousand cycles are 6.9 mm and 14.9 mm on both comparisons, respectively, indicating that the VLLs in these investigations are within medium- and softer-compacted ballast track models, respectively (medium-compacted: 5–10 mm, and softer-compacted: 10–18 mm, for 300 thousand cycles, as described in Figure 3.0-5).

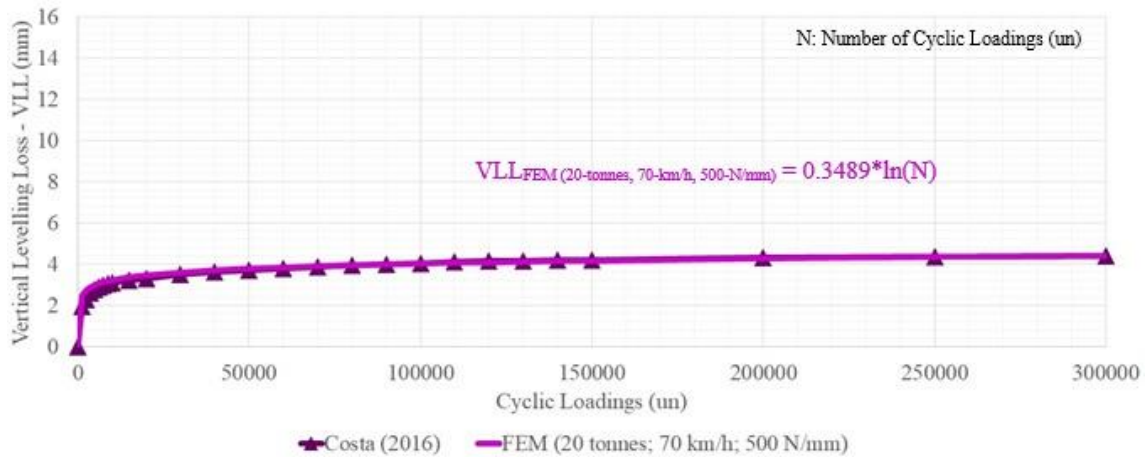


Figure 5.0-5. Comparison of VLLs between the regression performance (from the numerical model - FEM) and the triaxle experiment carried out by Costa (2016) under similar conditions (20-tonnes axle load, 70-km/h train velocity and 500-N/mm ballast tangent stiffness).

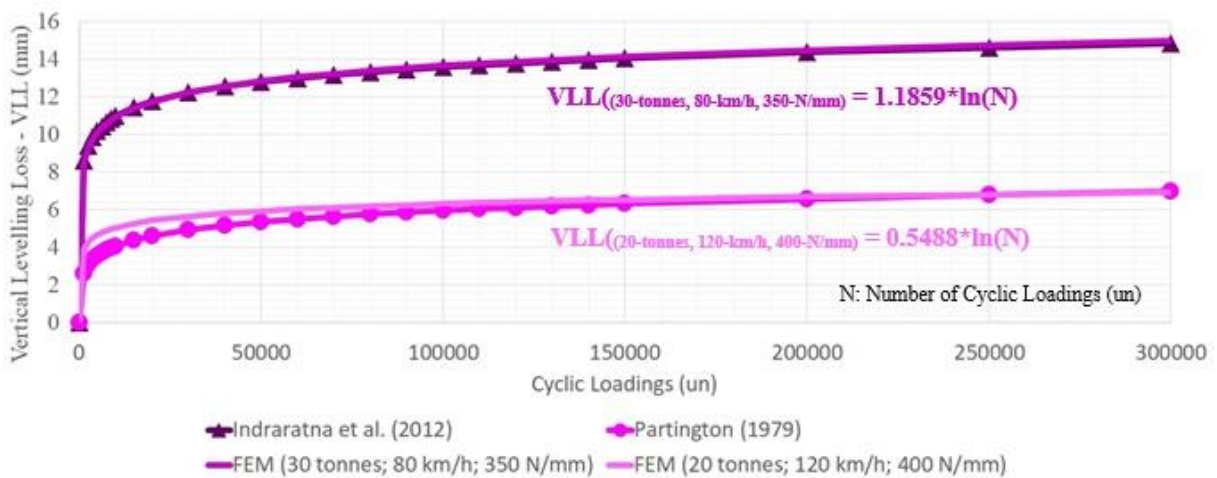


Figure 5.0-6. Comparison of VLLs between the regression performance (from the numerical model - FEM) and the studies carried out by Partington (1979) and Indraratna et al. (2012), under similar conditions, respectively (Partington: 20-tonnes axle load, 120-km/h train velocity and 400-N/mm ballast tangent stiffness; Indraratna: 30-tonnes axle load, 80-km/h train velocity and 350-N/mm ballast tangent stiffness).

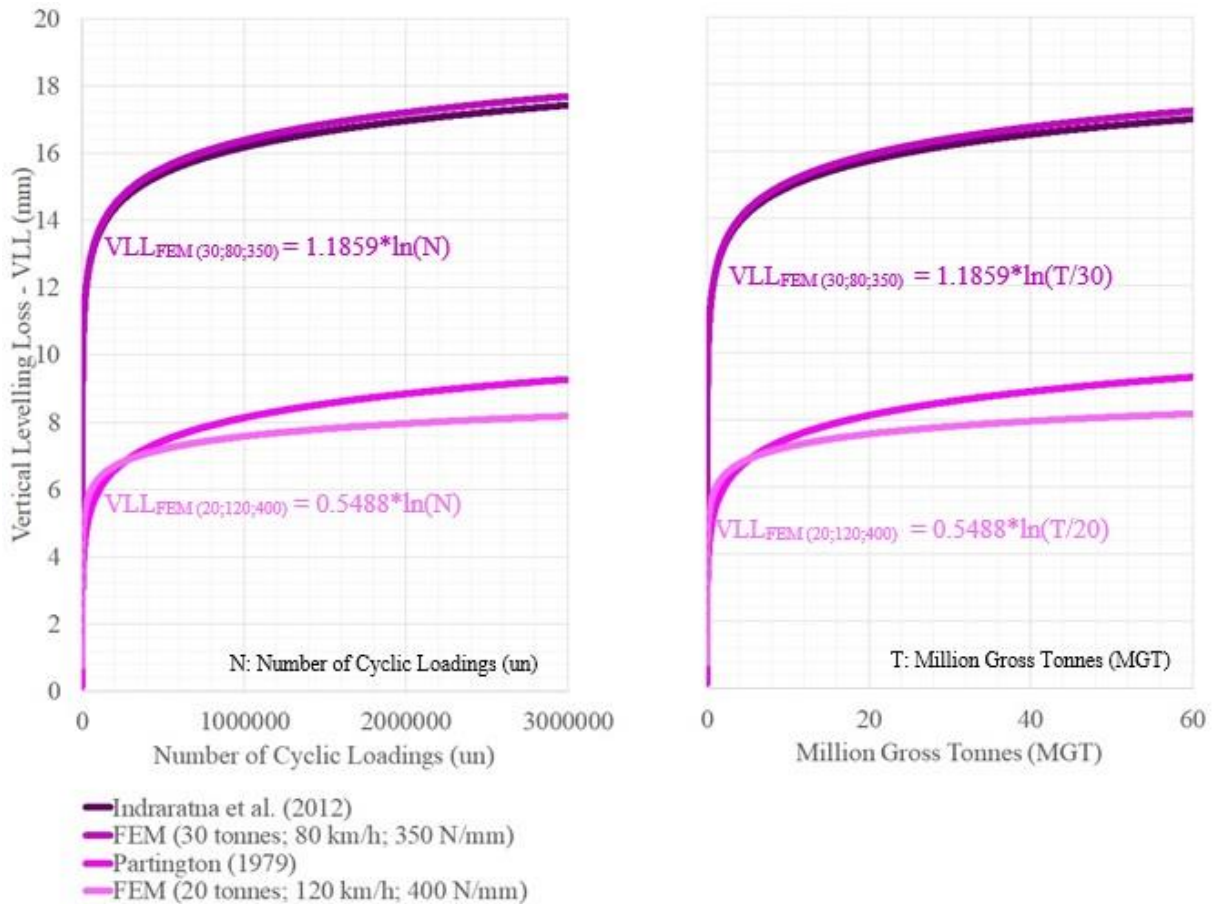


Figure 5.0-7. Comparison of VLLs between the regression performance (long-term) and the studies carried out by Partington (1979) and Indraratna et al. (2012) (left: < 3M cycles; right: < 60 MGT).

In order to extend the validation of the model beyond 300 thousand cycles, the regression performance is applied under 3 million cyclic loadings or 60 MGT for 20-tonnes axle load. That amount of load represents four months of traffic in a heavy haul railway in Brazil such as the EFC. Figure 5.0-7 shows the increase of VLLs of both investigations – Partington (1979), and Indraratna et al. (2012) – and their similarities or contrasts with the FE models. The FE model under 30- tonnes axle load continues to adjust well to Indraratna’s study (VLL = 17.7 mm and 17.4 mm, respectively, for 3 million cycles). Regarding the 20-tonnes FE

model, it is identified a slight difference (approximately 1 mm) to Ref. Partington's work (VLL = 8.2 mm and 9.3 mm, respectively, for 3 million cycles), meaning that it presents a reasonable match between them.

5.5. Parametric Approach

From the previous comparisons undertaken between the FE models and other studies – section 5.4, it is possible to conclude that the proposed model can be validated and, consequently, applied to different railway dynamic conditions (including operation, vehicle, and track). This section is related to the track performance under key parameters, as indicated in Figure 4.0-6 (Chapter 4). It is focused on varying those predefined parameters (axle load, train velocity and ballast tangent stiffness) onto the model to identify the rate of VLL and its behaviour, under cyclic loadings.

Similarly, to section 5.3 – the model validation, in this section numerical studies are performed, and their outcomes are also extracted, analysed, and regressed over LN functions. The “ a_{VLL} ” coefficients of those VLL regression equations represent the rate in which that specific railway track under cyclic loadings loses its vertical levelling. In other words, those coefficients (a_{VLL}) simply mean how much, how faster, where and when those railway tracks are going to be degraded and, consequently, to have achieved their VLL thresholds (alert limit or intervention limit, as highlighted by BS-EN-13848-6 (2014)). The rates of VLL (a_{VLL}) under the influence of ballast tangent stiffness and axle load are presented in Figures 5.0-8 and 5.0-9, respectively.

For the railway tracks dominated by ballast tangent stiffness, as shown in Figure 5.0-8, the rates in which the track geometry loses its vertical levelling climb considerably for low ballast tangent stiffness (softer ballast) – from 0.5 to 2.4 (500%) – when the axle load increases

from 15 on (light loads) to 40 tonnes (heavy-haul loads), respectively, as expected, in an extreme situation. Those predictable accelerated degradations are intrinsically related not only to the contact force (axle load) but also to the high initial ballast void (loose ballast) applied into the track without a proper tamping (compaction). On the other hand, the “ a_{VLL} ” coefficients for high ballast tangent stiffness (stiffer ballast) rise slightly or even maintain steadily, depending on both the axle load and the train velocity. As it can be observed, the rates increase from 0.2 to 0.5 between 15-tonnes and 25-tonnes axle loads, respectively, on low train velocity – 60 km/h (Figure 5.0-8a). Those coefficients maintain steadily (around 0.5) between 25-tonnes and 30-tonnes axle loads on both 70-km/h and 80-km/h train velocities (Figures 5.0-8b and 5.0-8c), increase slightly (from 0.5 to 0.8) after 30-tonnes axle load on 100-km/h and higher train velocities (Figures 5.0-8d-5.8g). In practice, this behaviour is anticipated since the well-compacted crushed ballast below the rail side sleepers has a reduced initial void causing the increase of ballast density and, consequently, its strength, also altering its natural frequencies. That observation further attests the findings presented by Tutumluer et al. (2018), and Foster and Kulkarni (2021). Additionally, it is noted that, for example, on 70-km/h train velocity (Figure 5.0-8b), the rate of VLL raises from 0.4 to 0.6 (50%) if the axle load increases from 30 ton to 40 ton (30%), respectively – as intended by Carajás Railway (EFC), a heavy-haul railway company in Brazil, whose that kind of information might be taken into account to support the decision-maker.

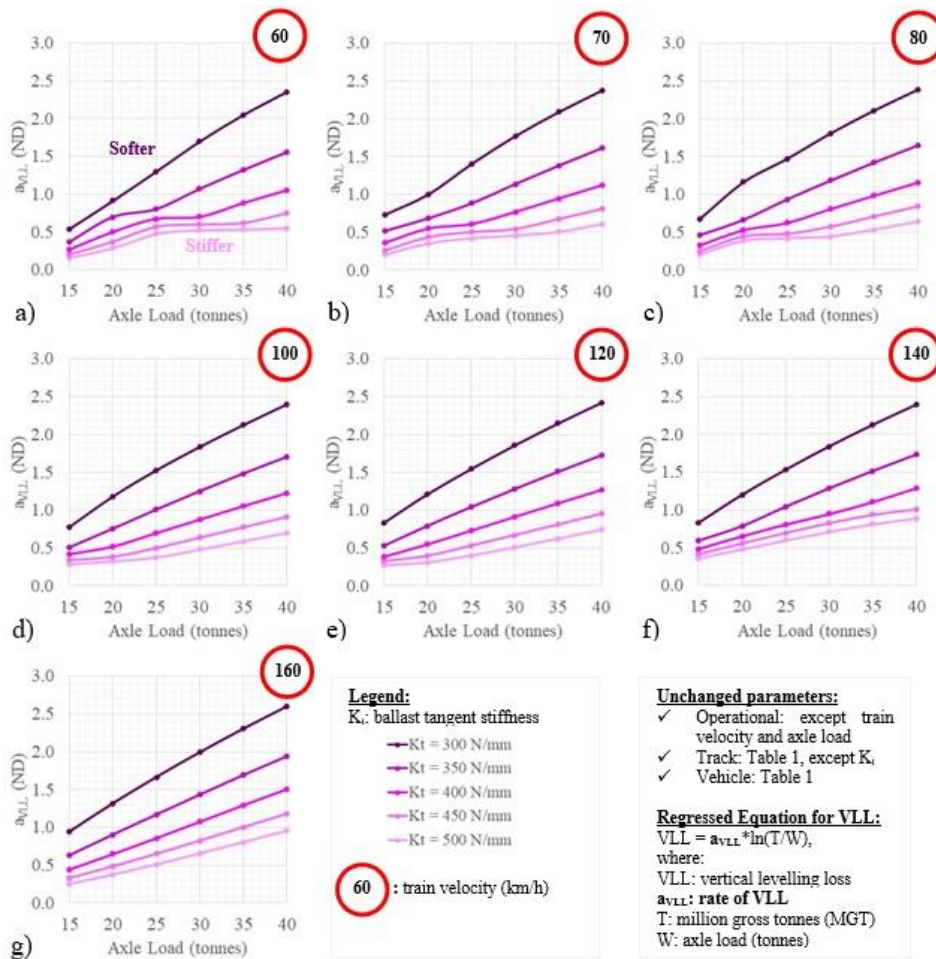


Figure 5.0-8. Rates of VLL (a_{VLL}) in function of axle load under different ballast tangent stiffnesses (K_t) and train velocities.

The rates of VLL can also be discussed looking into the axle load effect, as illustrated in Figure 5.0-9. The “ a_{VLL} ” coefficients are plotted in function of ballast tangent stiffness for each established train velocity. A similar trend of VLL degradation can be found when either increase the ballast tangent stiffness or the train velocity indicating that the axle load plays a key role on track geometry degradation, as mentioned before. However, as it can be observed from Figure 5.0-9a, the influence of the axle load is reduced on 60-km/h train velocity for high ballast tangent stiffness showing a slight increase of the rate (< 0.1) even when the axle load is

boosted from 30 to 40 tonnes. It means that the wheel-rail contact force on 40-tonnes axle load, for example, has already explored the dynamic strength of a well-compacted crushed ballast over time. Also, Figures 5.0-9b-5.0-9f depict that as faster as the train run, from 70 km/h to 140 km/h, the same behaviour can be identified – a small raise of the rate (< 0.1), although this behaviour moves onto the inferior neighbour axle load values as much as the train velocity increases (i.e., differ to 60-km/h train velocity, on 80-km/h train velocity and at high ballast stiffness – 500 N/mm, the “ a_{VLL} ” rises slightly when the axle load increases from 20 to 25 tonnes. In fact, that behaviour is related not only to the axle load (contact force) but also to the natural frequencies of the railway track, as pointed out by Esveld (2001). From Figure 5.0-9, it can also be seen that for softer ballast (at 300-N/mm ballast tangent stiffness), the command of axle load is evident though the rates of VLL behaviour indicates a variability depending on the train velocity.

To expand further the discussion regarding the influence of train velocity on the rate of VLL, Figure 5.0-10 is also presented. From the results shown in that figure and in complement to the previous analysis, the “ a_{VLL} ” coefficients do not present a straightforward tendency except when 40-tonnes axle load, 160-km/h train velocity and medium to softer ballast tangent stiffnesses are applied. This can be explained, according to Esveld (2011), by the fact that each structure (i.e., a ballasted railway track) has its own natural frequencies, which affect the vertical displacement and, consequently, the VLL under cyclic loadings. Furthermore, the rate of VLL at 160-km/h train velocity and at 40-tonnes axle load for a 500-N/mm ballast tangent stiffness illustrated in Figure 5.0-10a (0.95) indicates 160 km/h or over as a possible critical velocity, which is likely to give a very high dynamic amplification and the effect of the load travelling speed can therefore be maximized.

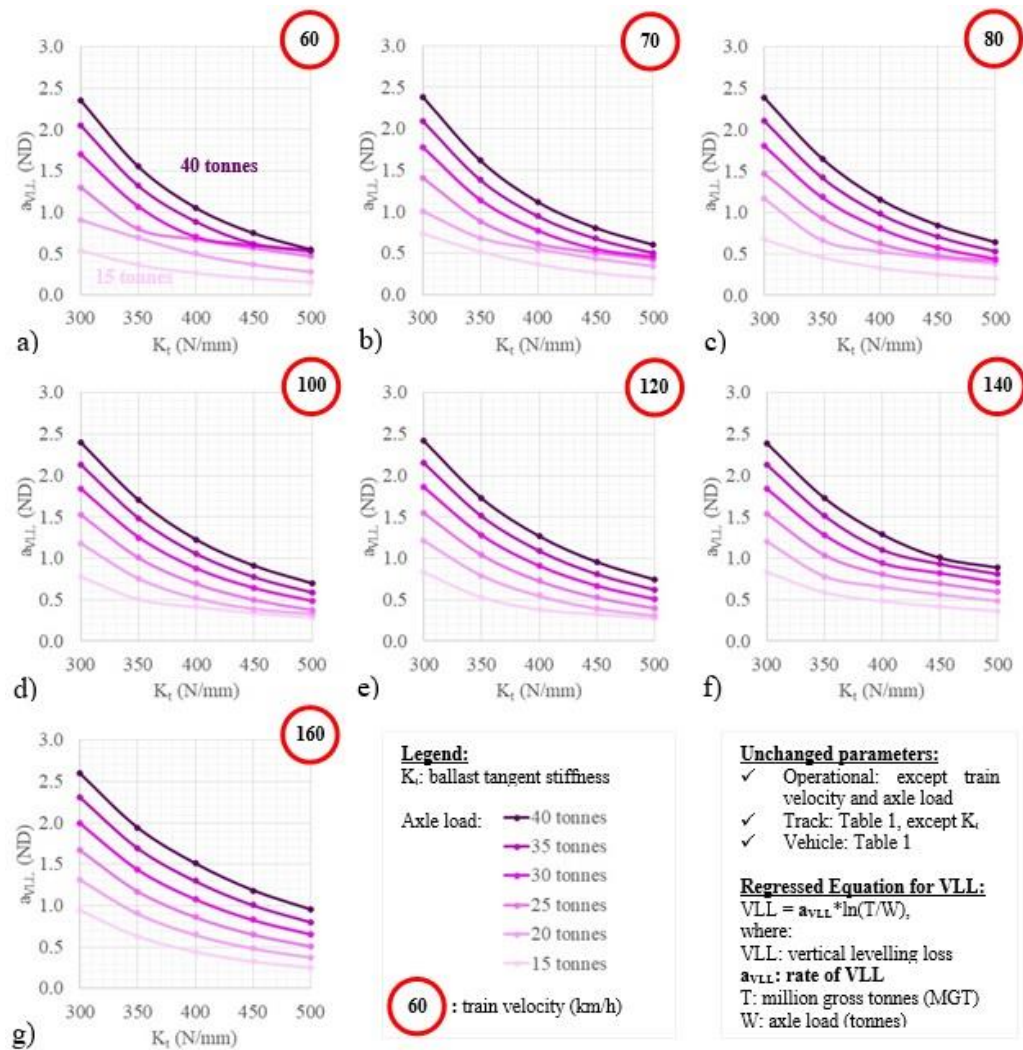


Figure 5.0-9. Rates of VLL (a_{VLL}) in function of ballast tangent stiffness (K_t) under different axle loads and train velocities.

On the other hand, it is noted that at 60-km/h and 70-km/h train velocities, and at the same 25-tonnes axle load for the same medium ballast tangent stiffness (400-N/mm; Figure 5.0-10c), the rates of VLL are, respectively, 0.7 and 0.6, indicating that lower speed not necessarily means low rate of track geometry degradation. This observation also finds resonance in Kempfert and Hu (1999), Esveld (2001), Sun (2015), and Mezher et al. (2016). Additionally,

from Figures 5.0-10b, 5.0-10d, 5.0-10f, 5.0-10h, and 5.0-10j, it is possible to note clearly the effect of train velocity on the rate of VLL, which, for example, presents high value (0.48) at 60-km/h train velocity and at 25-tonnes axle load for stiffer ballast (Figure 5.0-10b) if it is compared to 100-km/h (0.38), whereas for softer ballast (Figure 5.0-10j) at 25 tonnes and at 60 km/h and 100/km, the “ a_{VLL} ” are 1.30 and 1.53, respectively. Therefore, it can be concluded that the influence of train velocity on track geometry VLL is naturally associated to the ballast parameters, particularly, in this study, to the ballast tangent stiffness (K_t). Table 5.0-1 summarizes a_{VLL} coefficients for those track and operational conditions.

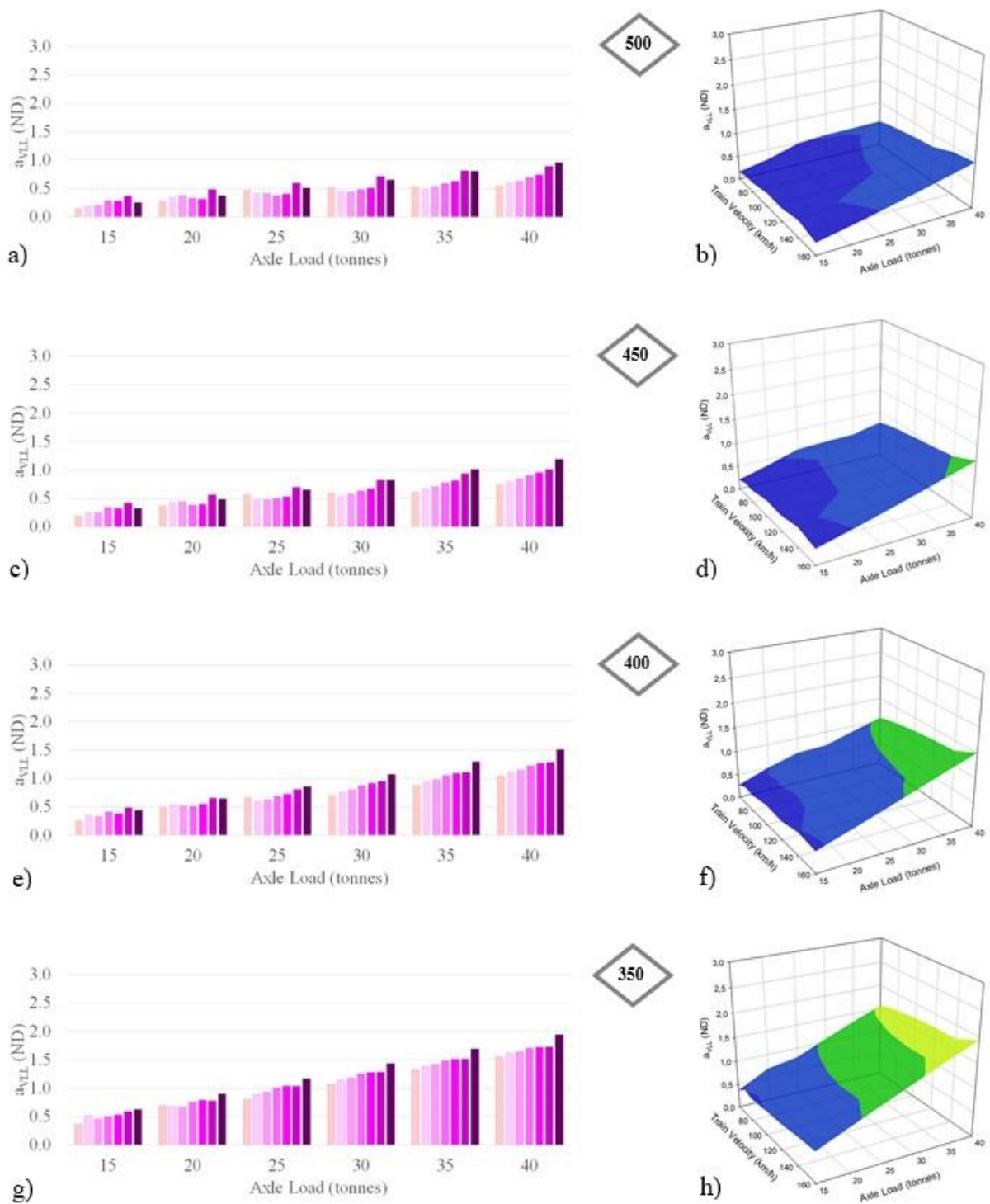


Figure 5.0-10. A joint visualization of rates of VLL (a_{vLL}) in function of the axle load under different train velocities and ballast tangent stiffnesses (top: stiffer ballast, and bottom: softer ballast tangent stiffness; left axle load and train velocity in 2D view, and right: in 3D view).

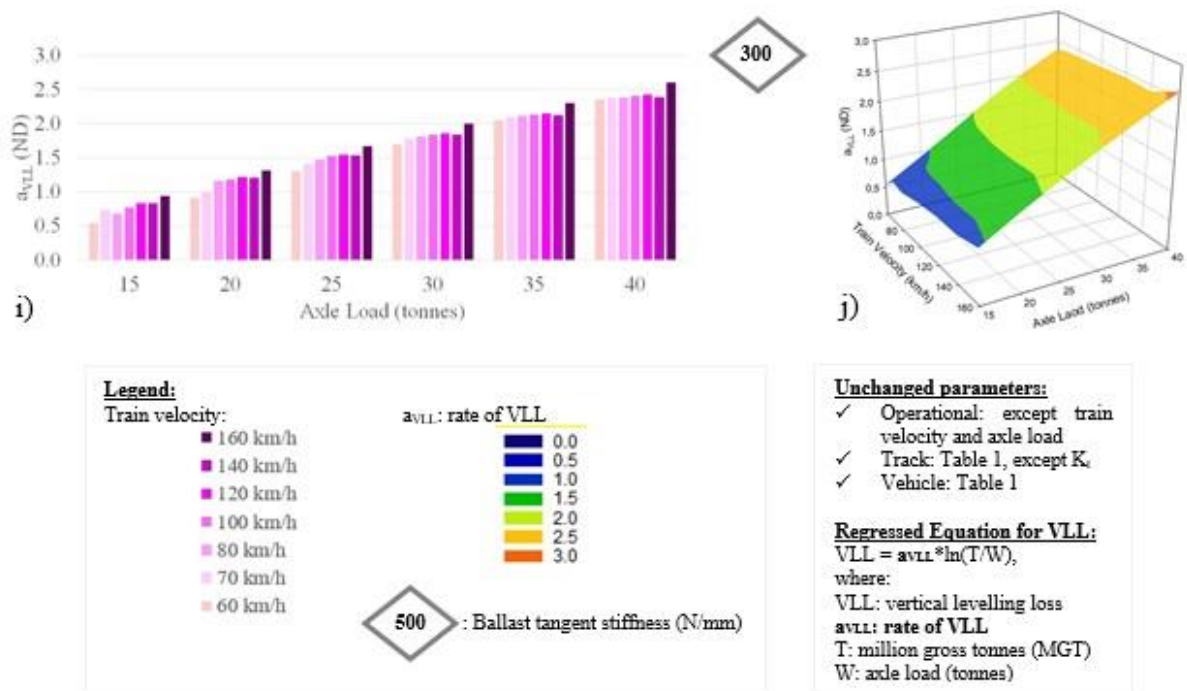


Figure 5.0-10. (Continued)

Table 5.0-1. A summary of aVLL coefficients for a specific railway track and operational conditions (Melo et al. 2022).

K _t (N/mm)	Axle load (tonnes)	Train Velocity (km/h)	a _{VLL} of LN function	Train Velocity (km/h)	a _{VLL} of LN function	Train Velocity (km/h)	a _{VLL} of LN function	Train Velocity (km/h)	a _{VLL} of LN function
300	15	100	0.7728	120	0.8326	140	0.8347	160	0.9422
	20		1.1787		1.2121		1.2049		1.3178
	25		1.5278		1.5459		1.5354		1.6658
	30		1.8386		1.8587		1.8426		1.9947
	35		2.1283		2.1520		2.1273		2.3051
	40		2.4034		2.4264		2.3936		2.6005
350	15	100	0.5037	120	0.5302	140	0.5898	160	0.6297
	20		0.7531		0.7941		0.7827		0.9054
	25		1.0073		1.0424		1.0400		1.1708
	30		1.2518		1.2808		1.2836		1.4350
	35		1.4849		1.5105		1.5126		1.6934
	40		1.7058		1.7284		1.7311		1.9423
400	15	100	0.4148	120	0.3849	140	0.4855	160	0.4440
	20		0.5157		0.5488		0.6540		0.6493
	25		0.6947		0.7285		0.8100		0.8608
	30		0.8748		0.9104		0.9479		1.0779
	35		1.0532		1.0911		1.1074		1.2970
	40		1.2259		1.2670		1.2915		1.5097
450	15	100	0.3434	120	0.3272	140	0.4187	160	0.3273
	20		0.3876		0.3966		0.5606		0.4850
	25		0.5027		0.5305		0.6990		0.6516
	30		0.6378		0.6694		0.8268		0.8271
	35		0.7743		0.8102		0.9370		1.0066
	40		0.9094		0.9523		1.0084		1.1837
500	15	100	0.2906	120	0.2768	140	0.3643	160	0.2526
	20		0.3282		0.3123		0.4822		0.3767
	25		0.3793		0.4022		0.6018		0.5105
	30		0.4820		0.5094		0.7140		0.6547
	35		0.5894		0.6220		0.8165		0.8028
	40		0.6972		0.7388		0.8916		0.9513

k_t: Ballast Tangent Stiffness; Ballast Elastic Stiffness (K_a): 45,430 N/mm; Ballast Yield Force (F_y): 500 N

Table 5.0-1. (Continued).

Kt (N/mm)	Axle load (tonnes)	Train Velocity (km/h)	a _{VLL} of LN function	Train Velocity (km/h)	a _{VLL} of LN function	Train Velocity (km/h)	a _{VLL} of LN function
300	15	60	0.5415	70	0.7322	80	0.6800
	20		0.9135		1.0035		1.1647
	25		1.3014		1.4091		1.4727
	30		1.6988		1.7758		1.8093
	35		2.0485		2.0956		2.1107
	40		2.3528		2.3829		2.3851
350	15	60	0.3662	70	0.5180	80	0.4627
	20		0.6959		0.6854		0.6653
	25		0.8024		0.8854		0.9359
	30		1.0702		1.1397		1.1859
	35		1.3188		1.3844		1.4249
	40		1.5558		1.6178		1.6504
400	15	60	0.2669	70	0.3655	80	0.3351
	20		0.5008		0.5524		0.5323
	25		0.6782		0.6114		0.6276
	30		0.7030		0.7704		0.8117
	35		0.8870		0.9464		0.9868
	40		1.0582		1.1193		1.1584
450	15	60	0.2034	70	0.2662	80	0.2568
	20		0.3744		0.4394		0.4516
	25		0.5715		0.5071		0.4833
	30		0.6027		0.5471		0.5801
	35		0.6218		0.6775		0.7134
	40		0.7535		0.8093		0.8459
500	15	60	0.1579	70	0.2019	80	0.2067
	20		0.2867		0.3489		0.3874
	25		0.4771		0.4196		0.4218
	30		0.5286		0.4532		0.4436
	35		0.5373		0.5035		0.5345
	40		0.5546		0.6062		0.6384

k_t: Ballast Tangent Stiffness; Ballast Elastic Stiffness (K_s): 45,430 N/mm; Ballast Yield Force (F_y): 500 N

5.7. Summary

This chapter discusses the results of numerical simulations and regression performances related to VLL in a heavy-haul ballasted railway track as proposed in the methodology’s Chapter (Chapter 4, Section 4.3). Initially, the vehicle-track model is simulated under cyclic loadings and operational parameters of 20-tonnes axle load and 70-km/h train velocity. The vertical rail displacements (VRDs) are analysed and plotted in a time-domain graphic to identify the maximum VRDs (MaxVRDs) in each 4-cycle load. The numerical results are regressed by a Napierian logarithmic (LN) function to provide an estimation of the MaxVRDs for cyclic loadings. The differences between each 4-cycle loads for a long-term behaviour of the

MaxVRD LN function are calculated and the result indicates the first term of that regressed expression as the VLL of track geometry.

The result is compared to different experiments under repeated loadings and similar operational and track indicating that the numerical-analytical model gives a reasonable match with those measured data. Therefore, the proposed model can be validated and, consequently, applied to different railway dynamic conditions. It is focused on varying those predefined parameters (axle load, train velocity and ballast tangent stiffness) onto the model to identify the rate of VLL and its behaviour, under cyclic loadings.

In summary, it can be concluded that the influence of train velocity on track geometry VLL in a smooth track is naturally associated to the ballast parameters. Also, for soft ballast, the command of axle load is evident though the rates of VLL performance indicates a variability depending on the train velocity. Nonetheless, a well-compacted ballast (high ballast tangent stiffness) has a positive effect by minimizing the VLL in a heavy-haul ballasted railway track. Therefore, this numerical-analytical approach can very well predict the VLL long-term performance considering not only the number of cycles or MGT but also the different dynamic conditions.

However, it is important to highlight that the study of VLL in this chapter (smooth track) is limited to track, vehicle, and operational condition as the sleeper support is not considered. To fully understand the effect of unsupported sleeper occurrences, the next chapter (Chapter 6) will discuss the results of numerical-analytical approach in unsupported-sleeper tracks.

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**EFFECT OF UNSUPPORTED-SLEEPER TRACK ON VERTICAL
LEVELLING LOSS**

This chapter presents the results and discussion of the application of an original numerical-analytical approach to predict ballasted railway track geometrical degradation focused on vertical levelling track geometric element in an unsupported-sleeper track. It briefly presents the subject under study and discusses the results obtained from numerical simulation and regression performance of VLL (Vertical Levelling Loss) considering the parameters obtained from a heavy-haul railway in Brazil. Also, to check whether the numerical model can be reliable for predicting the VLL, the validation of the model is investigated. Furthermore, this chapter discusses a parametric approach to investigate the effect of different axle loads and unsupported sleeper (US) configurations on VLL.

6.1. Introduction

From Chapter 3, an issue related to ballast settlement emerges to also influence the track geometrical vertical levelling degradation. Known as “unsupported sleeper” track condition (Figure 3.0-6 in Chapter 3), it occurs in over 50% of ballasted railway tracks (Sresakoolchai and Kaewunruen 2022) due to: (1) the differential ballast settlement, and (2) the high flexural stiffness of rails, as explained in Chapter 2. In this track condition, the rails remain suspended causing the formation of the track with hanging sleepers, which boosts the dynamic forces on a ballasted railway track as aforementioned. These forces are responsible for escalating the VLL under dynamic cyclic loadings by damaging the railway ballast in a vicious cycle (Melo et al. 2023a).

Many researchers have investigated the effect of unsupported sleeper on the track settlements, however their findings, despite of being interesting, are limited to dynamic elastic responses under monotonic loading. In general, they do not provide an accurate investigation of the effect of US on railway track VLL in a long-term behavior as pointed out in Melo et al. (2023a). Based on this, this study proposes the development of an innovative numerical-analytical method to predict track geometrical VLL considering not only the railway dynamic conditions but also the response of US under load cycles (Melo et al. 2023a).

6.2. Numerical Simulation

To verify whether the numerical model can provide reliable insight into the effect of US on track geometrical VLL, first the validity of the FEM (Finite Element Method) results regarding the wheel-rail contacts forces is studied considering monotonic loading, elastic behaviour of components, and traditional US track. It is verified the FEM model outcomes with the field experiments carried out by Azizi et al. (2021), under similar operational and track parameters.

In Azizi's field experiment, the ballasted track possesses wooden sleepers. The test track is of type 46E2/U33 rail profile with the density of $7,800 \text{ kg/m}^3$ and elasticity module of 210 GPa. Material properties of the sleeper are the density of 690 kg/m^3 , and elasticity module of 6,900 MPa. The wooden sleepers are 2.4 m in length, 0.2 m in width, and 0.1 m in thickness. The vertical stiffness of primary suspension is 1,126,000 N/m, and the masses of wheel-set, traction bogies, and half of car body are, respectively, 1,931 kg, 1,595 kg, and 27,665 kg (Azizi et al. 2021).

Azizi et al. (2021)'s track experiments were undertaken under 21-ton axle load and 70-km/h train velocity. To perform the effect of traditional US, the ballast beneath the sleeper is removed. Figures 6.0-1 and 6.0-2 show comparison of dynamic forces provided by the

numerical (FEM) and the field investigations. From those figures, the maximum difference is 6% at 5 US track. Therefore, the outcome from the developed model gives a reasonable match with the measured data in the field tests.

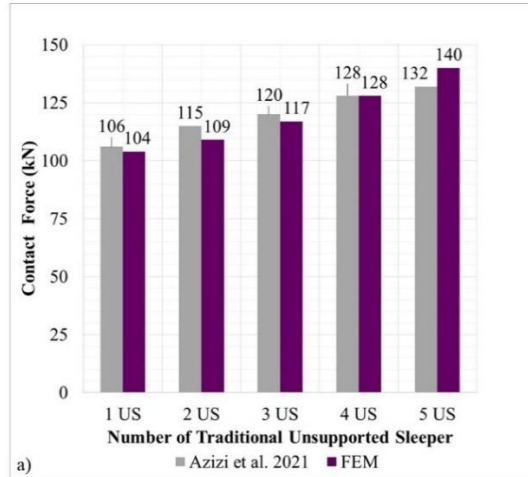


Figure 6.0-1. Comparison of wheel-rail contacts forces between the numerical model (FEM) and the field experiments carried out by Azizi et al. (2021), under similar operational conditions (21-tonnes axle load, 70-km/h train velocity, and traditional US condition).

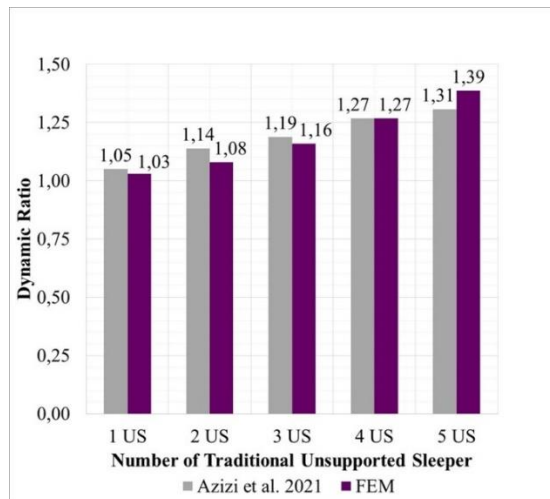


Figure 6.0-2. Comparison of dynamic ratio (dynamic force divided by static one) between the numerical model (FEM) and the field experiments carried by Azizi et al.

(2021), under similar operational conditions (21-tonnes axle load, 70-km/h train velocity, and traditional US condition).

From the proposed methodology in Chapter 4, Section 4.4, the track model is developed based on Melo et al. (2022)'s study (smooth track). The operational parameters (20, 30 and 40-ton axle loads, and 70-km/h train velocity) and the US track conditions (1-5 US with 1-5-mm gap) are applied, and the models are performed on HPC (High Performance Computing). Figure 6.0-3 illustrates the model performed using LS-Dyna FE (Finite Element) package.

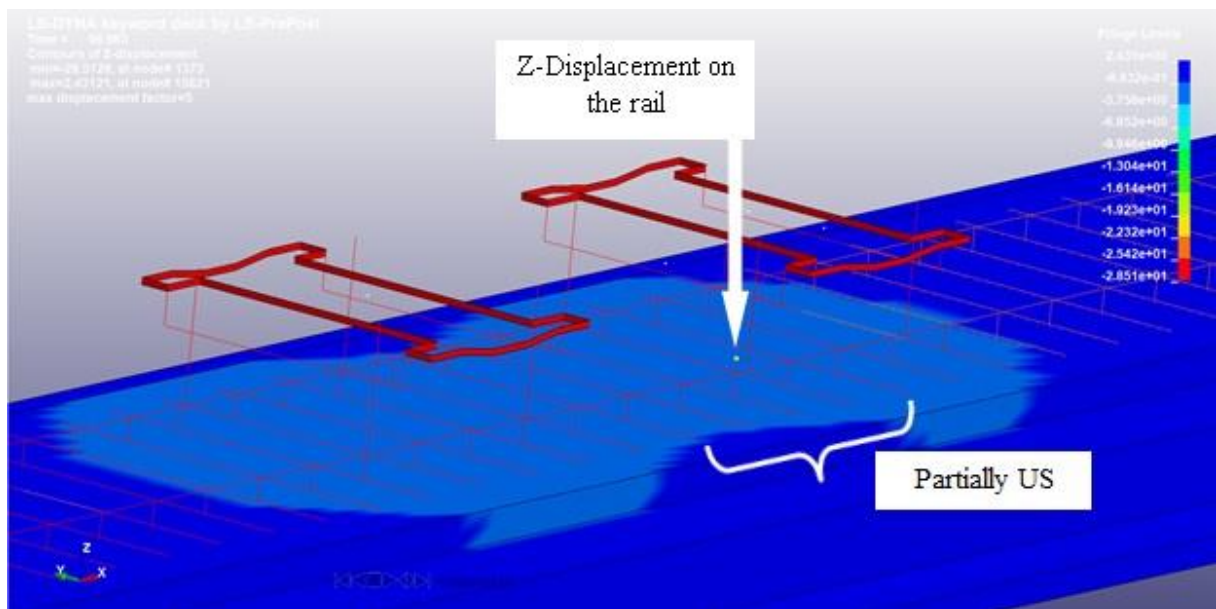


Figure 6.0-3. The track model performed under 40-tonnes axle load and 70-km/h train velocity (in details, the rail FE node displacement, and the indication of the 5 US sleepers with 5-mm gap).

The vertical rail displacements (VRDs) are numerically generated by the sum of elastic-plastic displacements on wheel-rail contact in vertical direction ('Z-Displacement' in Figure 6.0-3) for each repeated load. The slope of those displacements represents how faster and deeper the track loses its vertical profile (Melo et al. 2022). The MaxVRD (maximum values of vertical

rail displacement) after each 4 repeated loads are identified to both track conditions: supported and US tracks. During that stage, the MaxVRD values, under repeated loadings (short-term), are regressed by a LN function to provide an estimation of the MaxVRD regression function for a smooth track. The coefficient of determination, denoted R^2 , of the LN expression under 40-ton axle load and 70-km/h train velocity is 0.9730, which indicates a good accuracy. The results for this step can be written as follows:

$$MaxVRD \left(40 \text{ tonnes}, 70 \frac{km}{h}, 250 \frac{N}{mm} \right) = 1.7982 * \ln(N) + 16.2246, \quad (6.1)$$

where “ $MaxVRD \left(40 \text{ tonnes}, 70 \frac{km}{h}, 250 \frac{N}{mm} \right)$ ” is the maximum vertical rail displacement under 40-tonnes axle load, 70-km/h train velocity and 250-N/mm ballast tangent stiffness, and “ N ” is the number of cyclic loadings.

As suggested by Melo et al. (2022), the differences between each 4-repeated loads for a long-term performance of the MaxVRD LN function are calculated. The outcome indicates that the first term of Equation 6.1 is related to the VLL. Thus, the track geometrical VLL for those railway operation conditions, and smooth track may be written as (Melo et al. 2022):

$$VLL \left(40 \text{ tonnes}, 70 \frac{km}{h}, 250 \frac{N}{mm} \right) = 1.7982 * \ln(N), \quad (6.2)$$

$$VLL \left(40 \text{ tonnes}, 70 \frac{km}{h}, 250 \frac{N}{mm} \right) = 1.7982 * \ln \left(\frac{T}{40} \right), \quad (6.3)$$

where “ $VLL \left(40 \text{ tonnes}, 70 \frac{km}{h}, 250 \frac{N}{mm} \right)$ ” is the vertical levelling loss (in mm) under 40-tonnes axle load, 70-km/h train velocity and 250-N/mm ballast tangent stiffness, “ N ” is the number of cyclic loadings, and “ T ” is the million gross tonnes (MGT).

Following on the proposed methodology in Chapter 4, Section 4.4, the US gap is modelled in an US track as a non-linear element indicating that no force acts until the clearance is ceased. Similar to that smooth track, the MaxVRD curve is identified for the US track as Figure 6.0-4 depicts. From FEM's outcomes, it is clearly possible to observe the effect of US on VRD, particularly during the first cyclic loadings.

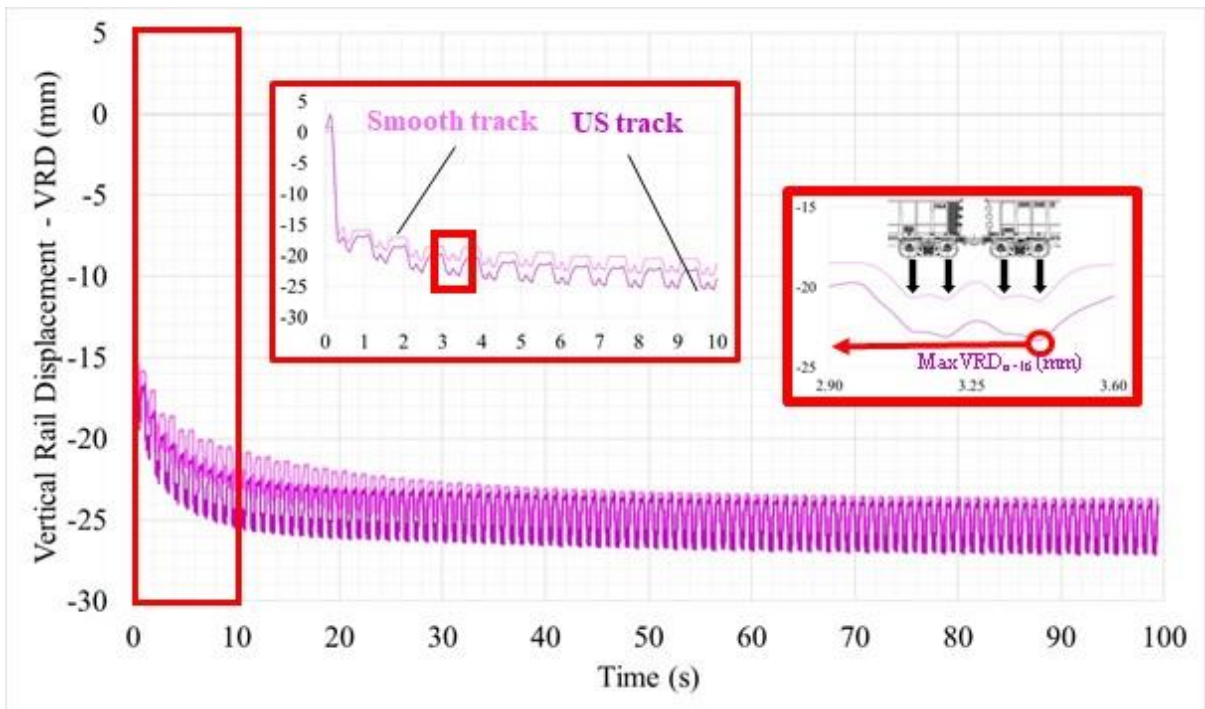


Figure 6.0-4. Vertical rail displacements (VRDs) on FEM under 40-ton axle load, 70-km/h train velocity, 5 US with 5-mm gap beneath sleepers (in details, the effect of superposition caused by the wheel loads on both US and smooth tracks).

6.3. Regression Performance

The ratio differences between the MaxVRD for both tracks (in each 4-cycle loads) are calculated, and a new curve is determined (in details in Figure 6.0-5). The ratio differences are regressed by a Power function from 200 cycles (stable phase) to define the function factor effect

of US for the uneven track as also indicated in Figure 6.0-5. The coefficient of determination (R^2) of the Power equation is 0.9707, which also indicates a good accuracy. The effect of US represented by ‘ μ ’ function shows that the values of the e_{US} coefficient and f_{US} coefficient are 0.0683 and -0.1453, respectively. The first coefficient (e_{US}) expresses the initial effect of US, whereas the second constant (f_{US}) reveals the rate of ‘ μ ’. That new curve expresses the response of US on MaxVRD and, consequently, on VLL over time. The non-linear characteristics of the performed models and the ratio differences between their MaxVRD are shown in Figure 6.0-3. Therefore, the VLL considering the effect of US may be updated as (Melo et al. 2023a):

$$nVLL = [1 + 0.0683 * (N)^{(-0.1453)}] * 1.7982 * \ln(N), \text{ for } 'N' \geq 200, \text{ or} \quad (6.4)$$

$$nVLL = \left[1 + 0.0683 * \left(\frac{T}{W}\right)^{(-0.1453)}\right] * 1.7982 * \ln\left(\frac{T}{40}\right), \text{ for } \left(\frac{T}{40}\right) \geq 200, \quad (6.5)$$

where ‘ $nVLL$ ’ is the ‘VLL’ considering the effect of US, ‘ N ’ is the number of repeated loadings, ‘ T ’ is million gross tons (MGT) and ‘ W ’ is the axle load (in tonnes).

From Figure 6.0-5, it can be observed that the difference between the MaxVRD curves suggests a clear response of the US. Initially, during the first cycles, the difference rises sharply in function of the existing gap underneath the sleepers, which indicates that the wheel-rail contacts forces for the uneven track overcomes the smooth track due the variation of dynamic forces (impact loadings) generated by the US. These dynamic loadings are transferred from the rails through rail pads and sleepers to damage the ballast beneath the sleepers for each load cycle. Therefore, the ballast under those extreme impact loadings starts to settle causing the losses of vertical profile on the top of the rails. It attests the effect observed in Zhang et al. (2008). After 25 cycles, the difference between them startlingly decreases suggesting that the effect of US commences to be reduced as the rail displacement becomes larger than the gap. It

can be noted that only after 200 cycles, the difference between the MaxVRD curves assumes a stable behaviour indicating a constant rate of influence related to the existing US condition.

Equation 6.4 presents the accumulation of the VLL for the real repeated loadings taking into consideration the effect of US. The VLL in the smooth track at both 10 thousand and 1 million cycles are approximately 16.5 mm and 24.8 mm, whereas the VLL in the US track are 16.9 mm and 25.1 mm, meaning that the US condition degrades the vertical profile in 1.8% and 0.9%, respectively. It also indicates that the dynamic influence of US reduces over time as deeper as the sleepers moves towards the ground due the ballast settlement, which overcomes the gap beneath sleepers. This observation is also identified in Augustin et al. (2003) when they explain the influence of poorly installed sleepers on the evolution of VLL.

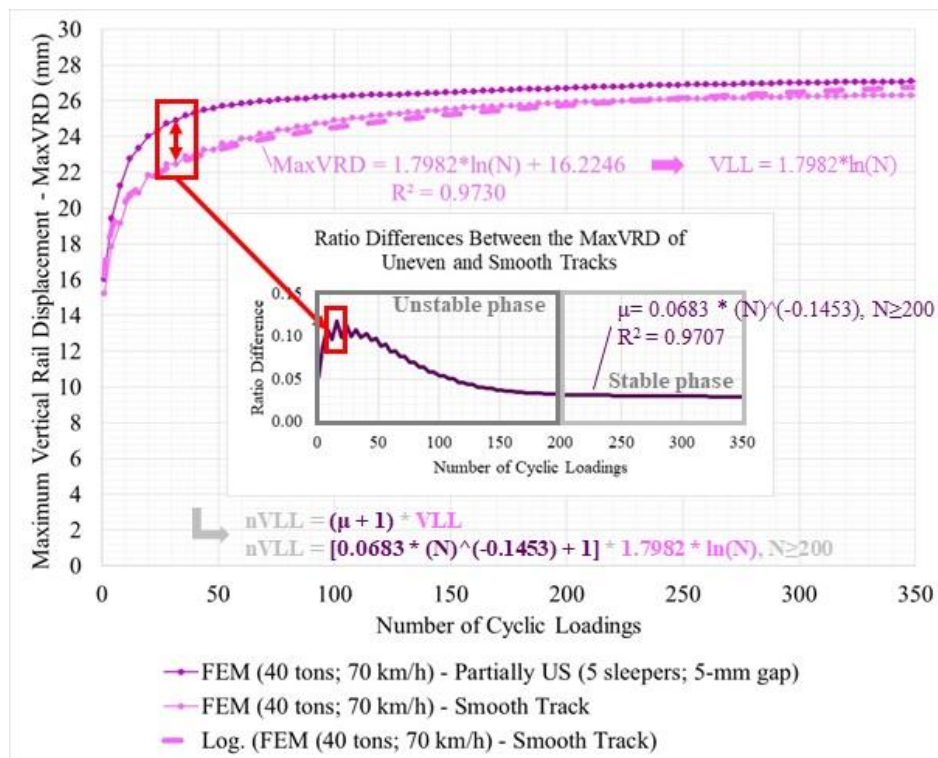


Figure 6.0-5. Maximum vertical rail displacement (MaxVRDs) on FEM under 40-ton axle load, 70-km/h train velocity, 5 US with 5-mm gap beneath sleepers (in details, ratio-differential graphic between the MaxVRD for US and smooth tracks).

6.4. Parametric Approach

To extend the investigation of the effect of US (μ) on VLL, different axel loads, and US conditions are applied on FEM under similar train velocity, vehicle characteristics, and track parameters as the previous simulation. Figures 6.0-6, 6.0-7, and 6.0-8 depict the comparisons of US function factor coefficients (e_{US} and f_{US}) for 20, 30 and 40-ton axle loads, respectively, at 70-km/h train velocity and in the range of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

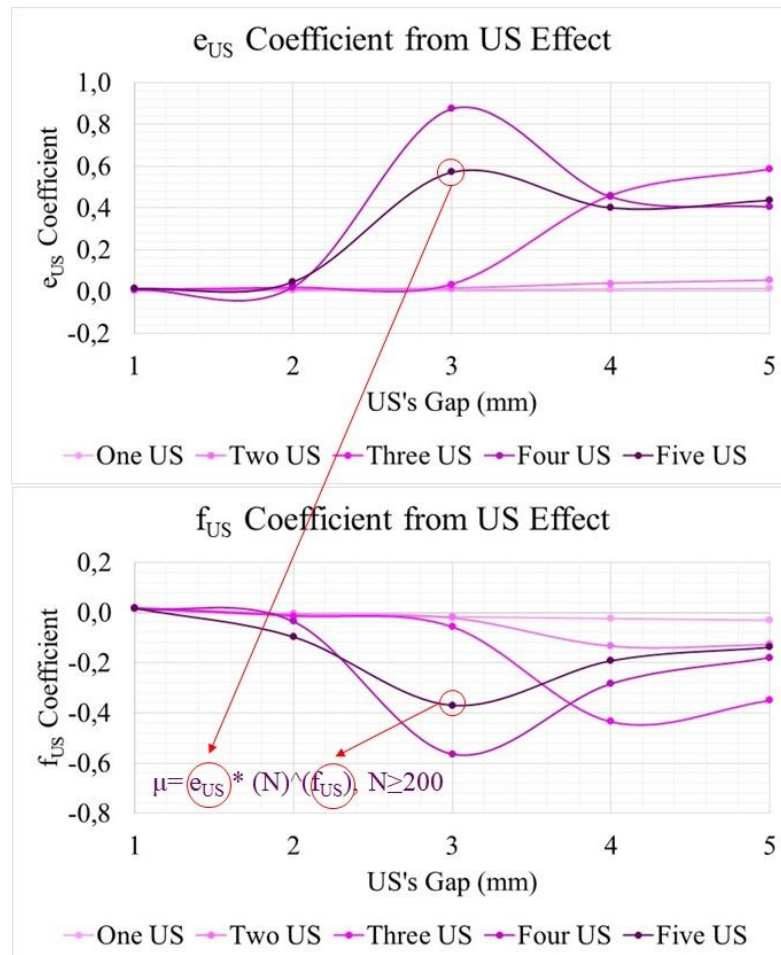


Figure 6.0-6. Comparisons of μ 's coefficients (e_{US} and f_{US}) for 20-tonnes axle loads, 70-km/h train velocity and the ranges of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

For the railway tracks dominated by 20-ton axle load (light railway), both e_{US} and f_{US} present a bell-shaped behaviour reaching the maximum and the minimum values, respectively, at 3-mm gap for 4 US. It does not mean necessarily the worst scenery; however, it indicates a critical configuration, which reflects the natural frequency of the ballasted railway track that is influenced not only by the 20-tonnes axle load but also by the track configuration (existing US).

On the other hand, if the axle load increases to 30 and 40 tonnes (Figures 6.0-7 and 6.0-8), the US function factor coefficients increase or decrease slightly until 3-mm gap for 1-5 US indicating that these configurations do not significantly alter the VLL. In turn, at 4-mm gap on and for 4-5 US, the effect of US for 30-ton axle load (heavy haul railway) increases sharply implying that track configuration might be their critical one. Besides, it is noted that the coefficients for 40-ton axle (extreme heavy haul railway) raise or reduce marginally at 4-mm gap on and 4-5 US suggesting that the vertical rail displacement for 40-ton axle load is much larger than the gaps beneath the sleepers.

The effect of US on track geometrical VLL can also be discussed looking at the long-term performance, as illustrated in Figures 6.0-9, 6.0-10, and 6.0-11, and Table 6.0-1. The differences (%) between the VLL for US track and smooth track are calculated based on Equations 4.3, 4.6, and 4.8 (from Chapter 4) at 3 million cycles (or 60 MGT, which represents the amount of 4 months of traffic in a typical heavy-haul railway) for the same parameters described above.

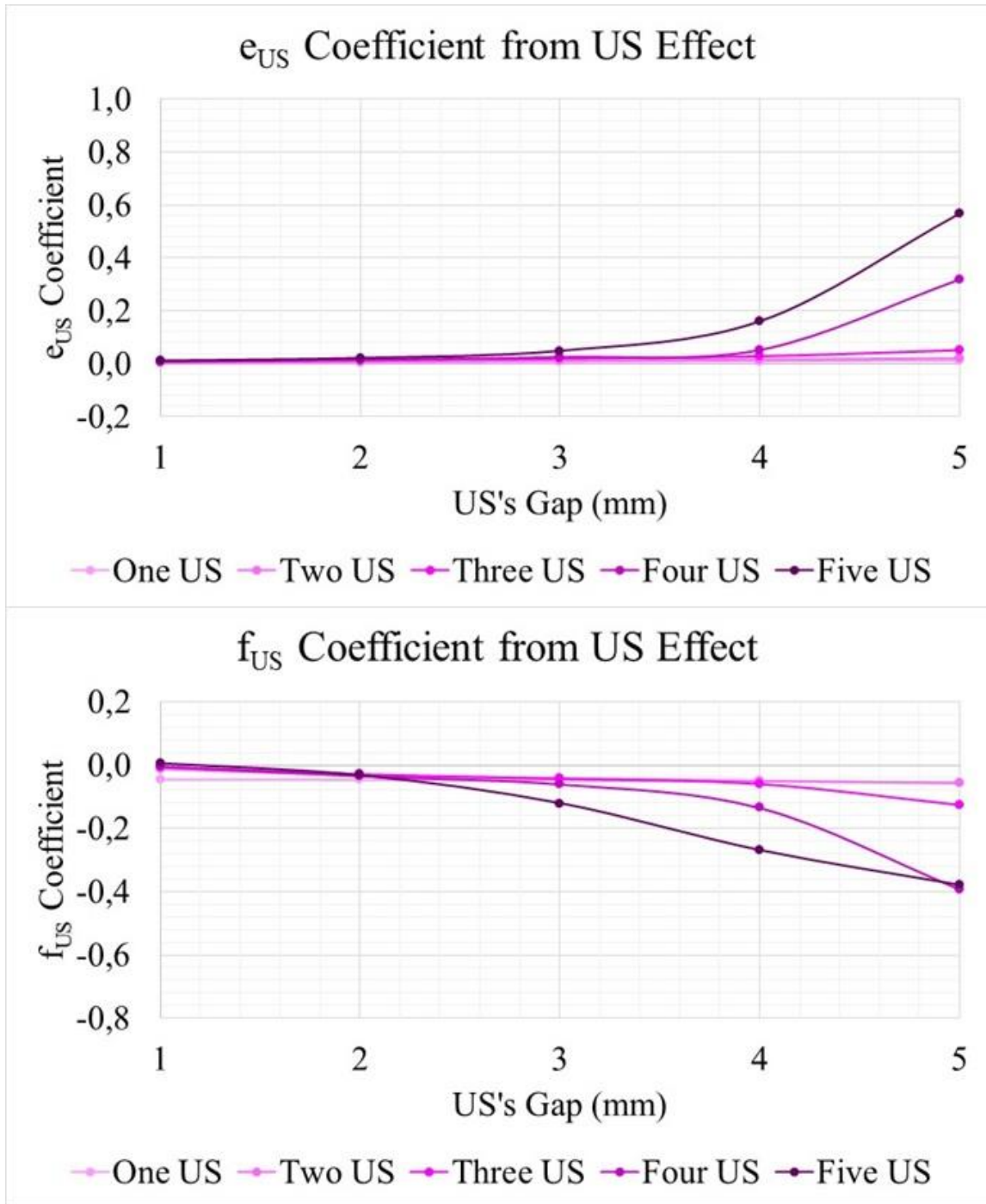


Figure 6.0-7. Comparisons of μ 's coefficients (e_{US} and f_{US}) for 30-tonnes axle loads, 70-km/h train velocity and the ranges of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

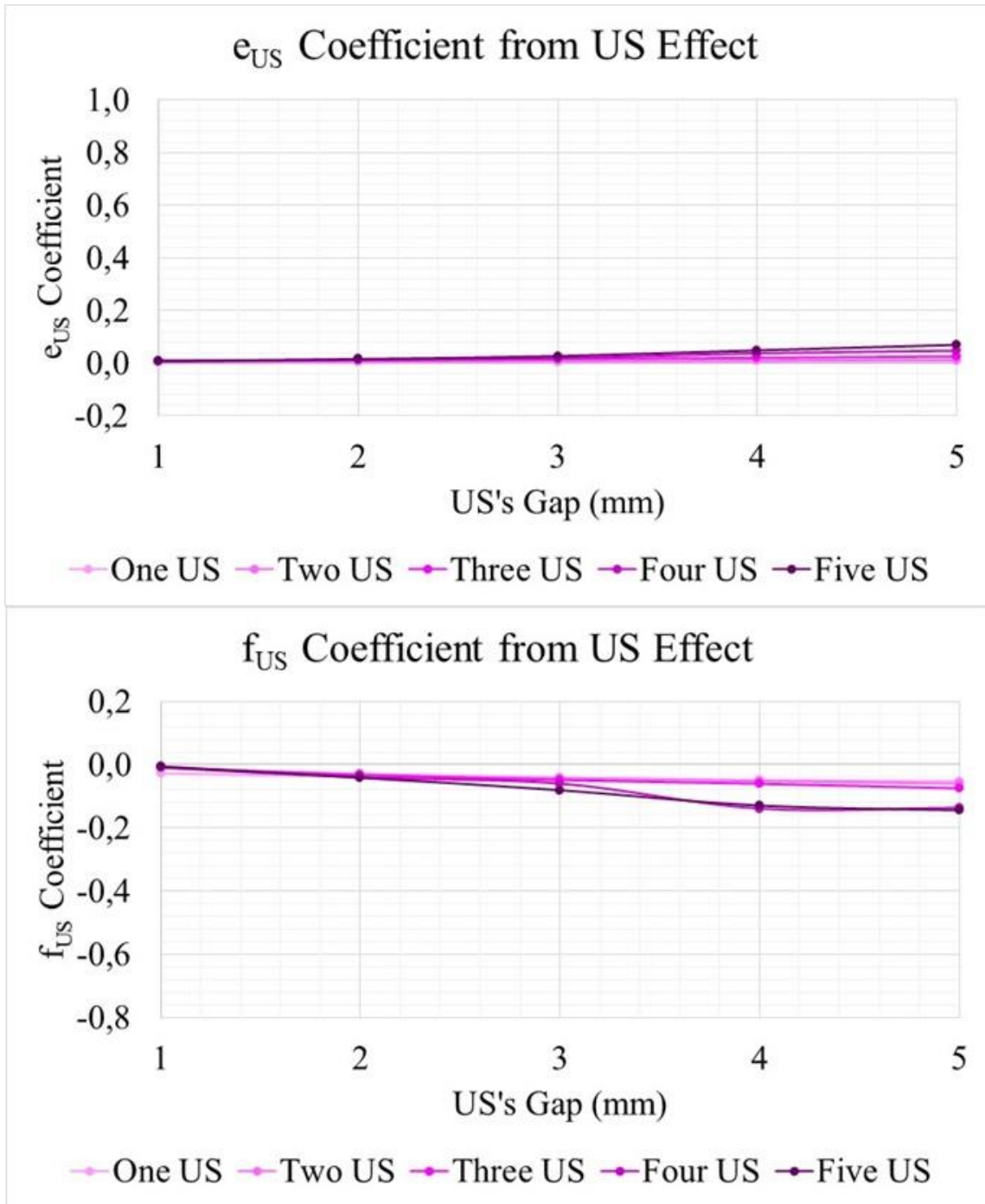


Figure 6.0-8. Comparisons of μ 's coefficients (e_{US} and f_{US}) for 40-tonnes axle loads, 70-km/h train velocity and the ranges of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

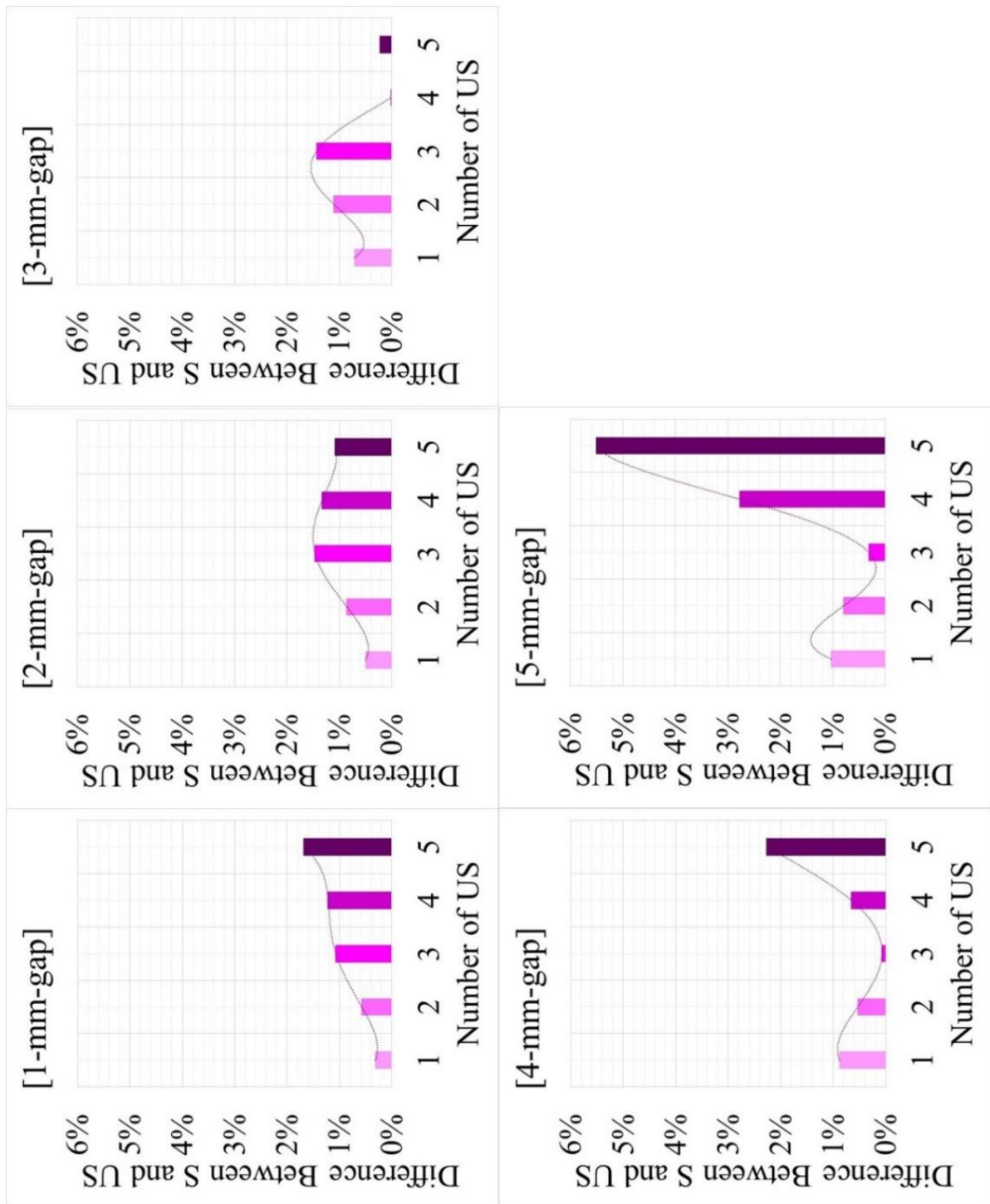


Figure 6.0-9. Differences in percentage (%) between VLL at 3 million cycles (MGT) for US and smooth tracks under 20-tonnes axle loads, 70-km/h train velocity and the ranges of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

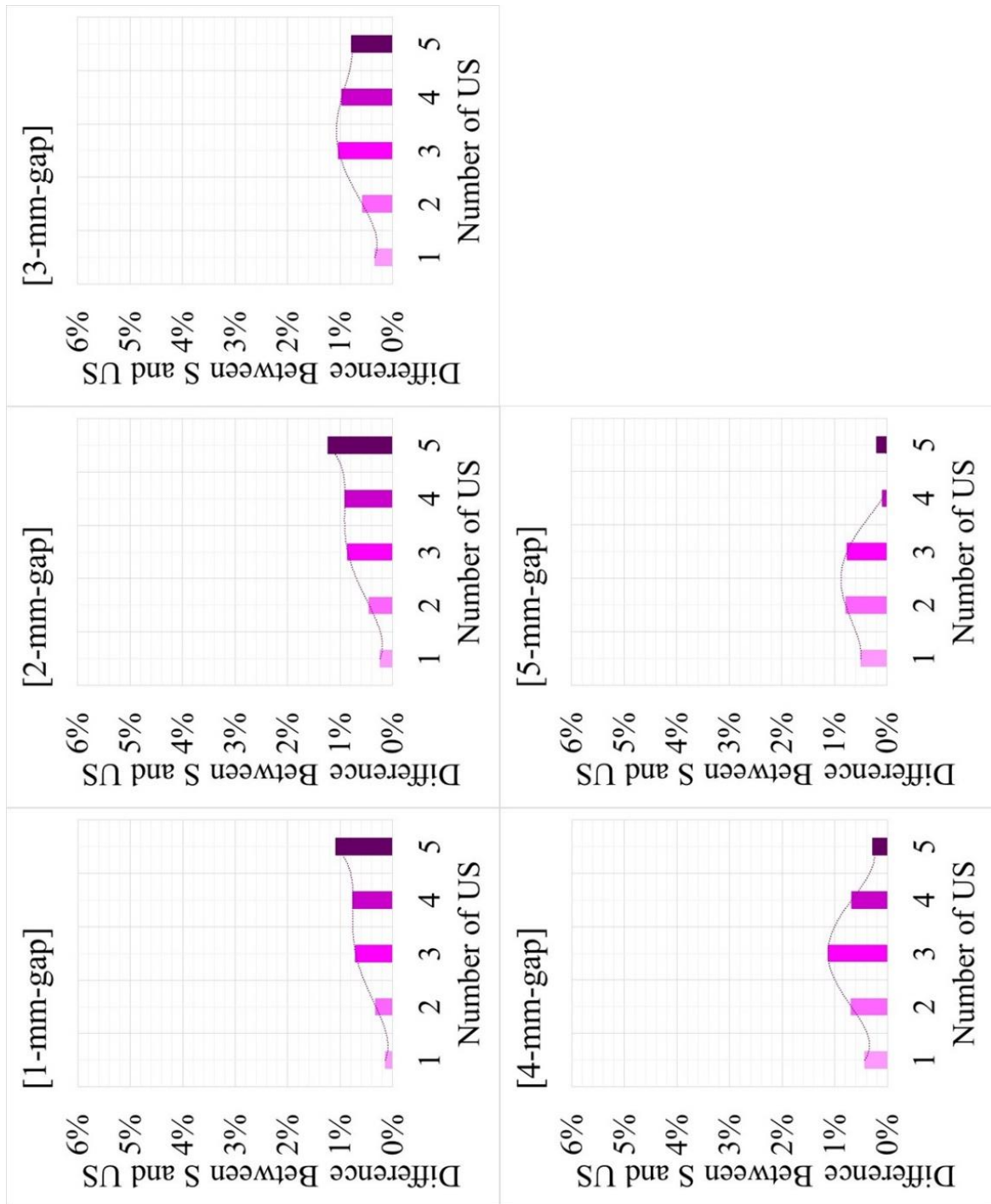


Figure 6.0-10. Differences in percentage (%) between VLL at 3 million cycles (MGT) for US and smooth tracks under 30-tonnes axle loads, 70-km/h train velocity and the ranges of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

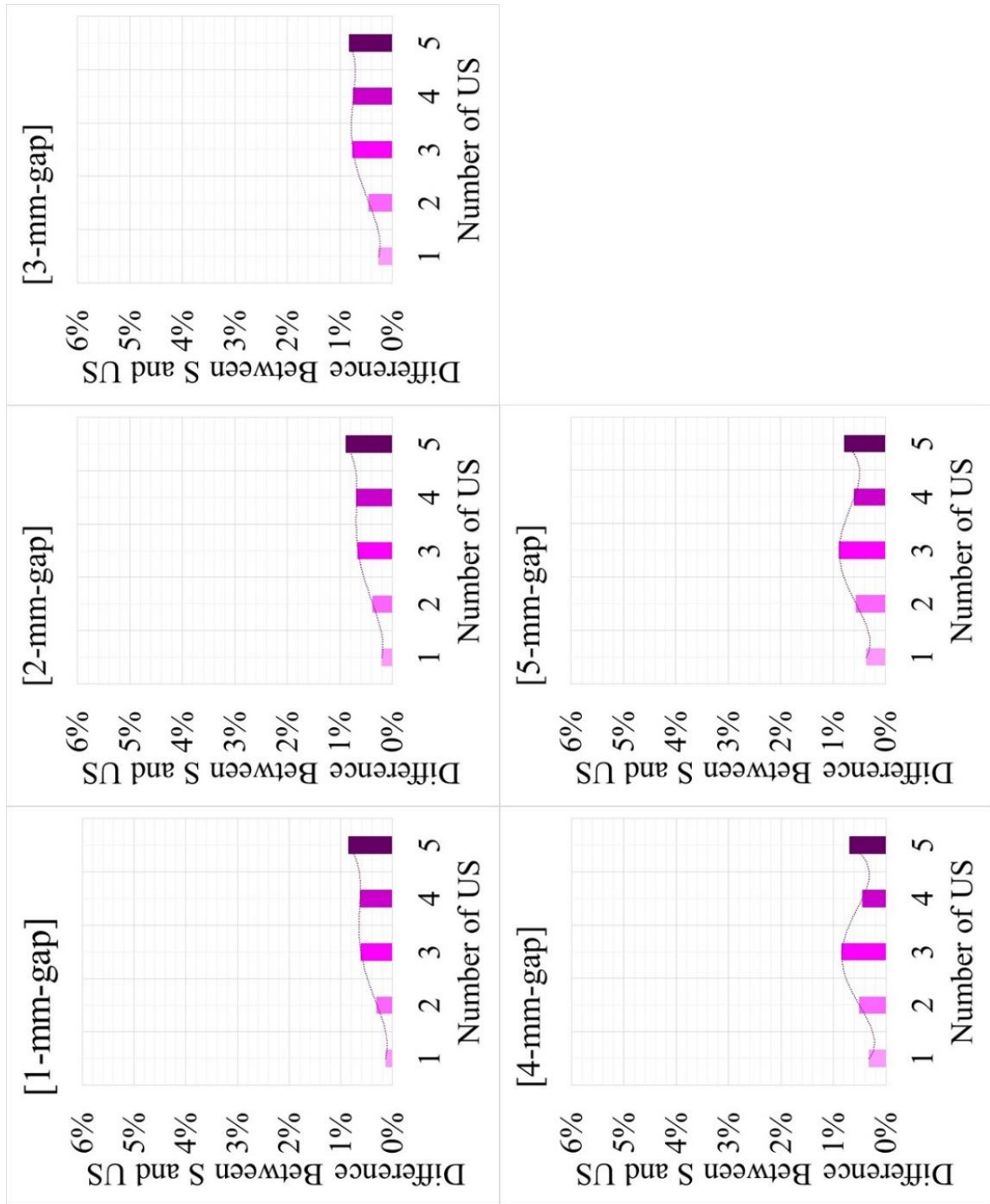


Figure 6.0-11. Differences in percentage (%) between VLL at 3 million cycles (MGT) for US and smooth tracks under 40-tonnes axle loads, 70-km/h train velocity and the ranges of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

Table 6.0-1. Summary of the differences in percentage (%) between VLL at 3 million cycles (MGT) for US and smooth tracks under 20, 30, and 40-tonnes axle loads, 70-km/h train velocity, and the ranges of 1 to 5 US with 1 to 5-mm clearance underneath the sleepers.

Partially US Effect on VLL at 3M Cyclic Loadings			Number of Partially US					Legend
			1	2	3	4	5	
US's Gap (mm)	20-ton axle load	1	0.31%	0.58%	1.07%	1.22%	1.68%	Effect ≤ 0.5%
		2	0.50%	0.86%	1.46%	1.33%	1.08%	0.5% < Effect ≤ 1.0%
		3	0.71%	1.11%	1.44%	0.02%	0.23%	1.0% < Effect ≤ 2.0%
		4	0.88%	0.53%	0.07%	0.66%	2.27%	2.0% < Effect ≤ 5.0%
		5	1.03%	0.80%	0.31%	2.77%	5.51%	Effect > 5%
	30-ton axle load	1	0.14%	0.32%	0.71%	0.76%	1.08%	Effect ≤ 0.5%
		2	0.24%	0.45%	0.86%	0.91%	1.23%	0.5% < Effect ≤ 1.0%
		3	0.34%	0.58%	1.03%	0.97%	0.78%	1.0% < Effect ≤ 2.0%
		4	0.43%	0.69%	1.13%	0.68%	0.29%	2.0% < Effect ≤ 5.0%
		5	0.50%	0.79%	0.76%	0.09%	0.20%	Effect ≤ 0.5%
	40-ton axle load	1	0.14%	0.30%	0.61%	0.63%	0.85%	Effect ≤ 0.5%
		2	0.20%	0.37%	0.66%	0.68%	0.89%	Effect ≤ 0.5%
		3	0.26%	0.45%	0.75%	0.74%	0.82%	Effect ≤ 0.5%
		4	0.31%	0.51%	0.84%	0.45%	0.69%	Effect ≤ 0.5%
		5	0.37%	0.57%	0.88%	0.60%	0.78%	Effect ≤ 0.5%

The trend of VLL degradation is not straightforward. It is observed, however, that the worst configuration for 20-ton axle load is at 5 US with 5-mm gap (5,51%). In turn, for 30 and 40-tonnes axle loads the unfavourable scenery is at 5 US with 2-mm gap (1.23% and 0,89%, respectively). Despite of this indicating that the axle load affects the VLL, the US condition plays a vital role to accelerate it. However, it is important to highlight that if the initial gap increases, for example, the effect changes and it can impact on VLL. As the US is commonly found in major locations, an acceptable configuration for the gap between the sleeper and the ballast can be specified for a minimum effect on VLL (thresholds) and, therefore, contribute as

a practical guideline to support the construction and maintenance activities in a ballasted railway track.

6.5. Conclusion

This study presents new insights into the effect of US on a ballasted railway track geometrical degradation after construction or maintenance activities. To investigate this phenomenon, a numerical study has been developed and validated focusing on the track geometrical VLL under cyclic loadings.

For a handling sleeper track, the investigation indicates that there is a noticeable influence of US on VLL. However, the influence is reduced as much as the axle load increases meaning that the dynamic wheel-rail contact force (impact loading) for a heavy haul railway (30 and 40-ton axle loads), for example, can lead the whole ballasted track settlement over time. On the other hand, for a light railway (20-ton axle load), if the vertical rail displacement is closer to the gap beneath the sleeper, the increase of impact loading is more influenced by the US conditions implying a relative and variable increment of vertical rail displacement.

Even though the insights demonstrate that the axle load effect is more pronounced, the US condition plays a significant role to contribute further on track geometrical VLL. As the US can be observed in railway tracks, the fact that it exists must be known to the track engineers and the acceptable configuration should be specified for a minimum effect on VLL (thresholds). Therefore, given that this novel improved method can accurately predict the effect of US on the track geometrical VLL considering different railway operational conditions (and configurations), their findings contribute to obtain new insights into track geometry degradation, and enhance the development of new practical maintenance and construction guidelines.

6.6. Summary

This chapter presents the results and discussion of the application of an innovative numerical-analytical method previously developed in Chapter 4, Section 4.4, to predict ballasted railway track geometrical degradation focused on vertical levelling track geometric element in an unsupported-sleeper track. It aims at investigating the effect of unsupported sleeper (US) on vertical leveling loss (VLL). The VLL equations obtained in this study permit accurately to identify the degree of the influence of US under different railway condition in a heavy-haul ballasted railway track, however this study focuses on different axle loads and US configurations. The investigation indicates that the dynamic influence of US reduces over time as deeper as the sleepers moves towards the ground due to ballast settlement, which overcomes the gap beneath sleepers in a poor vertical profile track. Also, it indicates that there are critical US configurations that reflect the natural frequency of a ballasted railway track considering not only the axle load but also the existing US. It is important to highlight that if the initial gap increases, the effect changes, and it can impact on VLL.

Results show that at 3 million cycles (or 60 MGT) the worst configuration for 20-ton axle load is at 5 US with 5-mm gap (5,51%), whereas for 30 and 40-ton axle loads is at 5 US with 2-mm gap (1.23% and 0,89%, respectively). This indicates that the axle load affects the VLL as expected, however, the US condition plays a significant role to accelerate it. Based on this study, the acceptable configuration of US can be specified for a minimum effect on VLL (thresholds) and, therefore, supports the development of practical maintenance guidelines to prolong the railway track service life.

It is obvious that the unsupported-sleeper track can result in a significant acceleration of VLL. Hence, prevention of handling sleeper occurrences, which is a major cause of ballast deterioration, is essential. The next chapter will investigate the effects of different initial track

irregularities on the dynamic response of railway ballast on VLL. The influence of SD (Standard Deviation) of VL (Vertical Levelling) on both rails (left and right rails) will also be studied in a parametric approach.

6.7. References

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INFLUENCE OF UNEVEN TRACK ON VERTICAL LEVELLING LOSS

This chapter presents the results and discussion of the application of an innovative numerical-analytical approach to predict ballasted railway track geometrical degradation focused on vertical levelling track geometric element in an uneven track (track with geometry irregularities). Also, it briefly presents the subject under investigation and discusses the influence of initial track irregularities (vertical profile defects) on VLL (Vertical Levelling Loss) obtained from numerical simulation and regression performance of the model of a heavy-haul railway in Brazil. To verify whether the numerical model can be reliable for predicting the VLL, the validation of the model is also investigated. Furthermore, similarly to Chapter 6, this chapter presents a parametric approach discussion to extend the study of dynamic influences of different patterns of ITI collected from a heavy-haul railway on VLL under cyclic loadings.

7.1. Introduction

From the previous chapters, particularly Chapters 2 and 3, the concept of an uneven ballasted railway track is related mainly to the vertical profile geometric element defects, which compound over 50% of track geometric irregularities in a typical ballasted railway as pointed out by Soleimanmeigouni et al. (2018). In all ballasted railway track after maintenance activities (e.g., tamping) is usual to identify initial vertical track irregularities as there is no smooth track in an actual railway system. This type of initial defects leads to amplify the vertical dynamic motions of the train (Adeagbo et al. 2021) overlapping the static wheel-rail force from the mass of the vehicle causing a progressive degradation of the railway track vertical profile (Dahlberg 2006), particularly due to the railway ballast damage.

Several studies for the last four decades have investigated empirically in specific site and railway condition the effect of initial track irregularities (ITI) on track settlements as described in Chapter 3, however none of these researchers have studied the dynamic influence of ITI (vertical profile) numerically under cyclic loadings and elastic-plastic behaviour of track components (e.g., plastic deformation of railway ballast) considering different railway operational conditions such as axle load, train velocity e track and vehicle parameters. Based on this knowledge gap, this study proposes the development of an original numerical-analytical method to predict track geometrical VLL considering not only the transient dynamic conditions but also the long-term effect of ITI under repetitive loading cycles over the service life. Similarly, to the previous method (Chapter 6), this approach can support the development of an efficient practical maintenance guideline recommending ITI thresholds for a minimum effect on VLL over time.

7.2. Numerical Simulation

The effect of initial track irregularities (ITI) on vertical levelling loss (VLL) over time under cyclic loadings and elastic-plastic behaviour of material (e.g., railway ballast plastic deformation) has never been evaluated in the past. As the experimental data on uneven tracks under cyclic loadings are also extremely limited, a typical heavy-haul ballasted railway track with monoblock concrete sleepers and artificial track irregularities is first considered for validation of the model. The results of wheel-rail contact forces from FEM (Finite Element Method) are validated against a previous experimental study carried out by Gadhve and Vyas (2022) under similar vehicle, track, and operational conditions. Wheel has a radius of 0.46 m with S1002 profile. Rails have UIC 60 profile with 1:40 cant. The modulus of elasticity of rails is 210 GPa and Poisson's ratio is 0.3. The wheelset, bogie, and half of the body masses are,

respectively, 1,200 kg, 2,615 kg, and 16,000 kg. Vertical stiffness of primary spring (1st suspension) is 544.57 kN/m. The train runs over tracks at constant velocity of 72 km/h (Gadhav and Vyas 2022).

The dynamic forces are investigated considering monotonic loading, elastic behaviour of vehicle and track components, and artificial track irregularities set by the PSD following ERRI-B176’s standard ERRI-B176 1993). When contrasted to the experiments carried out by Gadhav and Vyas (2022), the FEM model outcomes present acceptable matches with those measured data, in which the maximum differences related to the minimum and maximum vertical contact forces are approximately 3% and 2%, respectively. Table 7.0-1 presents a comparison between the values of wheel-rail contact forces from previous study (the Gadhav and Vyas’s experiment) and the current investigation.

Table 7.0-1. Comparison between wheel-rail contact forces provided by the numerical investigation (FEM) and the Gadhav and Vyas’s experiment.

Study	Contact Force (kN)	
	Minimum	Maximum
Gadhav and Vyas [43]	48.00	57.00
FEM	46.50	56.00
Difference (%)	3.23	1.79

In this study, the railway track model has been developed based on Melo et al.’s study (smooth track) (Melo et al. 2022) considering different operational conditions such as axle load (20, 30 and 40 tonnes), train velocity (60, 70, and 80 km/h), and ITI (two sets of track irregularity SD: 0.48 and 3.23 mm). Figure 7.0-1 illustrates the two typical sets of ITI registered by RC (Recording Car) based on AREMA’s standard (AREMA 2019), which are input to the

track model performance on LS-Dyna to calculate the dynamic forces and the track cumulative displacement under cyclic loadings. This permits the track engineer to evaluate the influence of ITI on VLL.

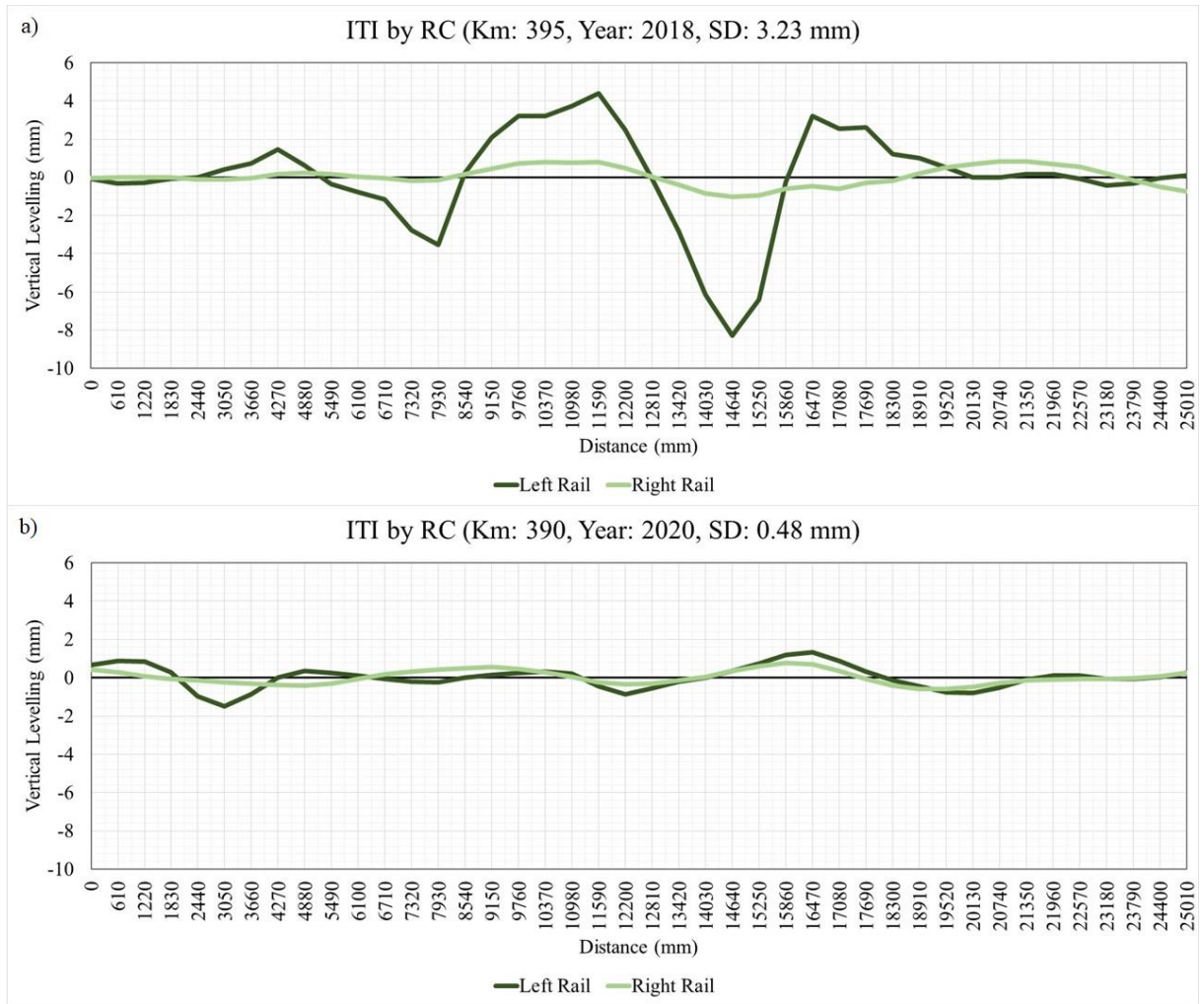


Figure 7.0-1. Vertical track irregularities registered by RC in 25-m railway track: (a) Km 395 in 2018 (SD: 0.48 mm), and (b) at Km 390 in 2020 (SD: 3.23 mm).

The vertical rail displacements (VRDs) are numerically calculated in vertical direction ('Z-Displacement') on the top of each rail node for each repeated load. The slope of those displacements indicates the track longitudinal level loss over time (Melo et al. 2022). The

MaxVRD (maximum values of vertical rail displacement) after each 4 repeated loads are identified to both track conditions: smooth and uneven tracks. Figure 7.0-2 illustrates one of segments of study to numerically calculate the short-term behaviour of VRD (Vertical Rail Displacement), and Figure 7.0-3 depicts the comparison of VRD on FEM under 30-ton axle load and 60-km/h train velocity for both the smooth and the uneven ($SD = 0.48$ mm) tracks.

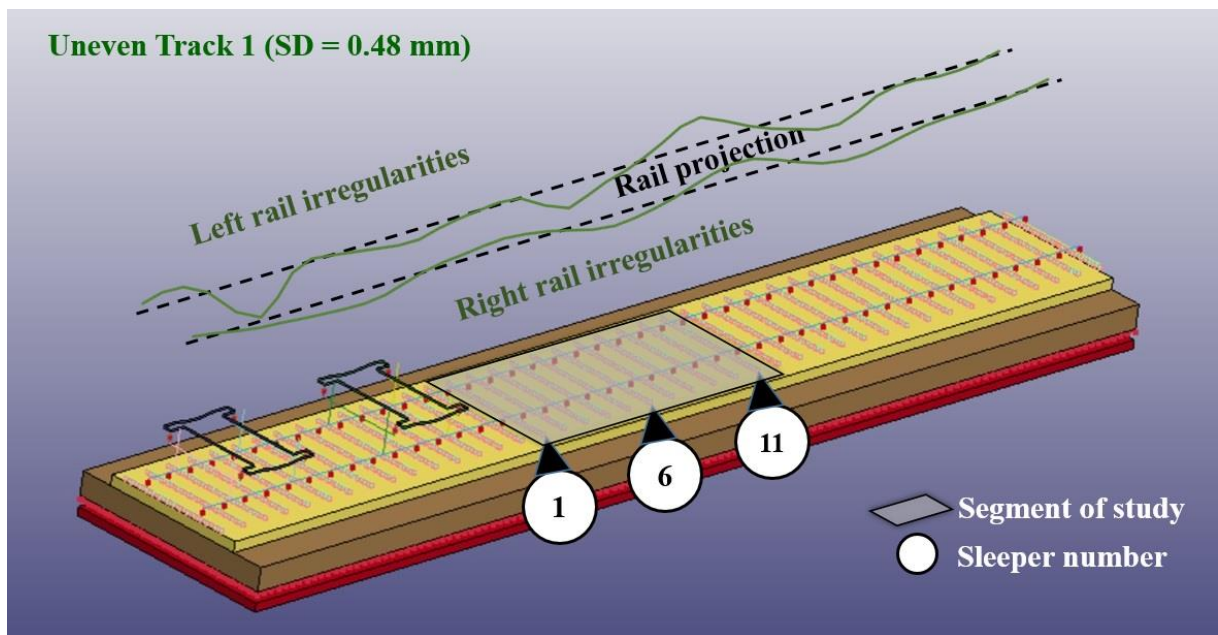


Figure 7.0-2. Segment of study to numerically calculate the short-term behaviour of VRD and MaxVRD on FEM under 30-ton axle load and 60-km/h train velocity for both the smooth and the uneven ($SD = 0.48$ mm) tracks.

From Figure 7.0-3, it can be observed clearly the effect of ITI on VRD, which escalates in function of the vertical profile irregularity progress on the top of right rail of the sleeper number 11, for example. This indicates that the wheel-rail contact forces for the uneven track overcame considerably those of smooth track due to the variation of dynamic forces (impact loads) generated by the roughness as expected. These dynamic loadings are transferred from

the rails through rail pads and sleepers to damage the ballast beneath the sleepers for each load cycle. Therefore, the ballast under those dynamic forces starts to settle substantially causing the losses of longitudinal level on the top of the rails. It corroborates the effect observed in Augustin et al. (2003), but it has not been proved numerically or experimentally before. These new findings are considerable better than the previous ones as they can support not only the development of predictive models under diverse operational railway conditions but also fill the knowledge gap related to the specification of experiments (numerical, field or laboratory) to coordinate the track geometrical degradation prediction as pointed out by Melo et al. (2022).

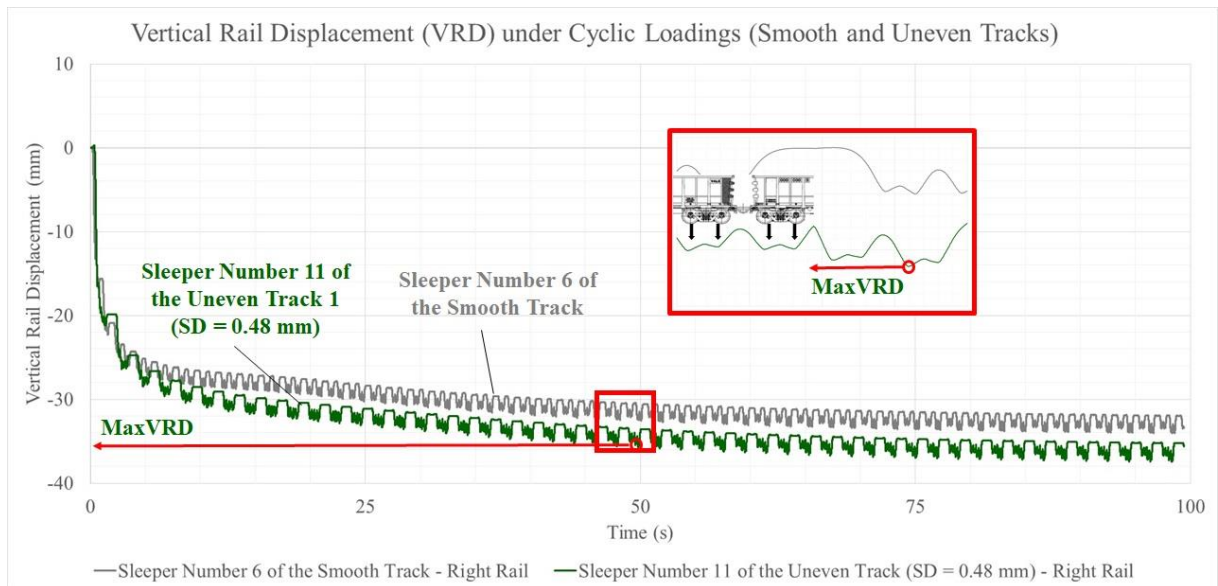


Figure 7.0-3. Comparison of VRD on FEM under 30-ton axle load and 60-km/h train velocity for both the smooth and the uneven (SD = 0.48 mm) tracks (in detail: the MaxVRD).

7.3. Regression Performance

In this section, the MaxVRD values, under repeated loadings (short-term), are regressed innovatively by a LN function to better estimate the MaxVRD regression function for a smooth

track. This finding provides new insights about capturing numerically on FE analysis the elastic-plastic behaviour of a railway ballast, and consequently, the vertical profile geometrical degradation of a ballasted railway track under cyclic loadings. The coefficient of determination, denoted R^2 , of the LN expression under regular operation of a heavy-haul railway (30-ton axle load and 60-km/h train velocity) is 0.9368 in the smooth track, which indicates a good accuracy. The results for this step can be written as follows (Melo et al. 2022):

$$MaxVRD \left(30 \text{ tonnes}, 60 \frac{km}{h}, 150 \frac{N}{mm} \right) = 3.3310 * \ln(N) + 14.7691, \quad (7.1)$$

where “ $MaxVRD \left(30 \text{ tonnes}, 60 \frac{km}{h}, 150 \frac{N}{mm} \right)$ ” is the maximum vertical rail displacement under 30-tonnes axle load, 60-km/h train velocity and 150-N/mm ballast tangent stiffness, and “ N ” is the number of cyclic loadings.

As previously suggested by Melo et al. (2022), the differences between each 4-repeated loads for a long-term performance of the MaxVRD LN function are also calculated. The outcome indicates that the first term of Equation 7.1 is related to the VLL. Thus, the track geometrical VLL for those railway operation conditions, and smooth track may be written as (Melo et al. 2022):

$$VLL \left(30 \text{ tonnes}, 60 \frac{km}{h}, 150 \frac{N}{mm} \right) = 3.3310 * \ln(N), \quad (7.2)$$

$$VLL \left(30 \text{ tonnes}, 60 \frac{km}{h}, 150 \frac{N}{mm} \right) = 3.3310 * \ln \left(\frac{T}{30} \right), \quad (7.3)$$

where “ $VLL \left(30 \text{ tonnes}, 60 \frac{km}{h}, 150 \frac{N}{mm} \right)$ ” is the vertical levelling loss (in mm) under 30-tonnes axle load, 60-km/h train velocity and 150-N/mm ballast tangent stiffness, “ N ” is the number of cyclic loadings, and “ T ” is the million gross tonnes (MGT).

Following on the proposed methodology, the ITI are modelled in an uneven track as non-linear features and, similarly to that smooth track (Equation 7.1), the MaxVRD curves are identified for two types of ITI sets and regressed by LN function. It is important to note that the forces that act on each rail node above the sleepers exceed the usual dynamic forces (from smooth track) due to those irregularities. The coefficients of determination (R^2) of the LN equation for each MaxVRD node curve on the top of both left and right rail in the uneven track segments of the study (Figure 7.0-2) varies from 0,8604 to 0.9697 depending on the sleeper position, which also indicates a satisfactory accuracy. The section in this study is strategically centralized in the track segment model along 11 consecutive sleepers. The non-linear characteristics of the performed models (smooth and uneven tracks) are shown in Figures 7.0-3 and 7.0-4. Therefore, the VLL can be updated for each node along the rails based on Equations 4.11 or 4.12 (from Chapter 4, Section 4.5) and their respective coefficients calculated as described on Table 7.0-2 for 30-ton axle load and 60-km/h train velocity.

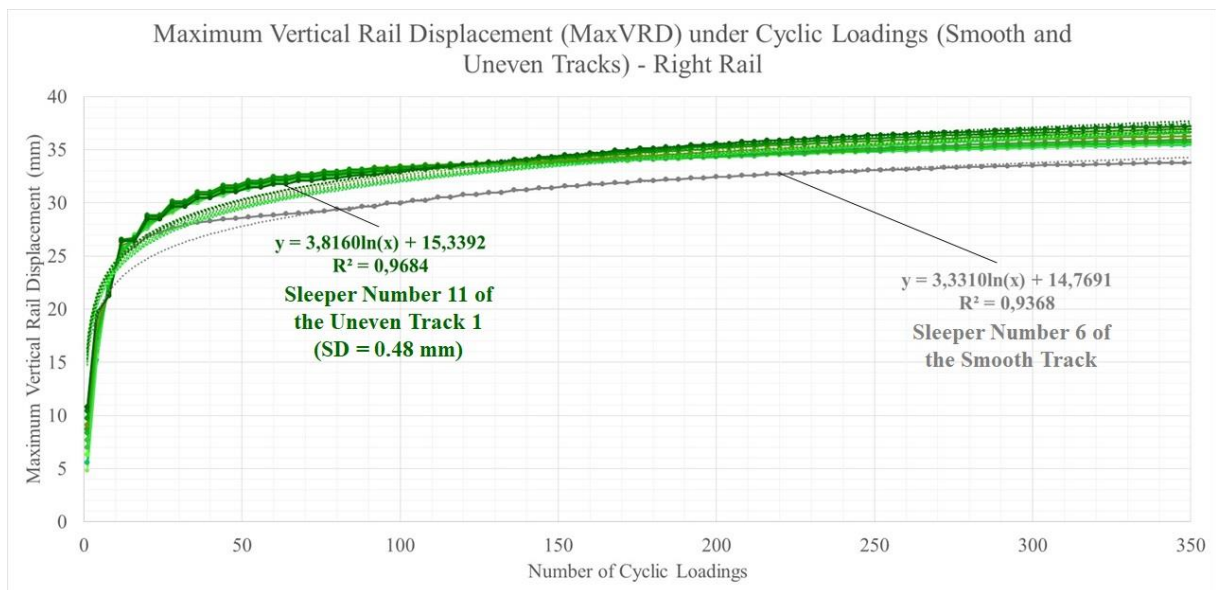


Figure 7.0-4. Comparison of MaxVRD on FEM under 30-ton axle load and 60-km/h train velocity for both the smooth and the uneven (SD = 0.48 mm) tracks.

Figure 7.0-4, in turn, illustrates the influence of ITI on MaxVRD curves, which are captured in function of (Melo et al. 2023b): (1) the ITI in each right rail node itself, (2) the ITI of the right rail neighbor nodes, and (3) the ITI in each node and neighbor nodes of the opposite rail (left rail). Accordingly, it shows numerically a clear effect of the ITI on MaxVRD, and consequently, on VLL, based on the $a_{(n)VLL}$ coefficients of the right rail (smooth track: 3,3310 and uneven track: 3,8160). It can also be observed that ‘ a_{nVLL} ’ coefficients for roughness track are different in each node on the top of rail along the segment of study depending on (Melo et al. 2023b): (1) the sleeper number position, (2) the initial node irregularity on the top of rail, and (3) the overlapped effect caused by the dynamic forces applied on adjacent sleepers. These effects are attested by Naeimi et al. (2015), particularly when the severity of the roughness increases. However, as above mentioned, earlier studies have not calculated the effect of ITI on VLL, which indicates that the new findings can be valuable for track engineers to estimate properly how much a ballasted railway track geometry degrades over time under dynamic cyclic loadings. Table 7.0-2 describes a summary of ‘ a_{nVLL} ’ coefficients for a typical heavy-haul railway operating under 30-tons axle load and 60-km/h train velocity, and two different sets of ITI. It indicates that the set of ITI with the highest SD of vertical profile (uneven track 2 – UT-2) degrades faster (37% on average) than that one with the lowest SD (uneven track 1 – UT-1). The exception is sleeper number 11 on the top left rail of the UT-2 (SD = 3,23 mm), which decreases 2.51%. This exceptionality may be explained by the low vertical profile deviation between the left and the right rails on that sleeper significantly reducing the wheel-rail contact force on it as also pointed out by Berawi (2013).

Table 7.0-2. A summary of ‘anVLL’ coefficients for a regular heavy-haul railway operation (30-tons axle load and 60-km/h train velocity) and two different sets of ITI.

Sleeper Number	‘anVLL’				Difference (%)	
	Uneven Track 1 (UT-1) (SD = 0.48 mm)		Uneven Track 2 (UT-2) (SD = 3.23 mm)		$\frac{[(C) - (A)] * 100\%}{(A)}$ Left Rail	$\frac{[(D) - (B)] * 100\%}{(B)}$ Right Rail
	Left Rail (A)	Right Rail (B)	Left Rail (C)	Right Rail (D)		
	1	5,4324	3,7403	6,3284	5,6574	16,49%
2	5,4050	3,6665	6,3357	5,6552	17,22%	54,24%
3	5,4279	3,6387	6,3472	5,6451	16,94%	55,14%
4	5,4604	3,6105	6,4900	5,6908	18,86%	57,62%
5	5,4798	3,5616	6,5564	5,8300	19,65%	63,69%
6	5,5023	3,5101	6,5771	5,9409	19,53%	69,25%
7	5,5372	3,5004	6,5133	6,0317	17,63%	72,31%
8	5,5914	3,5262	6,2730	6,0022	12,19%	70,22%
9	5,6919	3,5849	5,9371	6,0339	4,31%	68,31%
10	5,8498	3,6744	5,8957	5,9301	0,78%	61,39%
11	6,0684	3,8160	5,9161	5,8224	-2,51%	52,58%

Equations 4.11 or 4.12 (from Chapter 4, Section 4.5) combined with Table 7.0-2 permit to calculate the vertical levelling loss considering the effect of ITI in each node on the top of

both left and right rails above the sleepers in the segment of study. From 100 to 3 million cycles, it is possible to predict the vertical profile of each rail along the segment. Figures 7.0-5 and 7.0-6 illustrate the behaviour of the VLL from its initial stage (ITI by RC, $N = 0$) to 3 million cycles (approximately 60 MGT in a typical heavy-haul railway) for both low SD of ITI ($SD = 0.48$ mm) and medium SD of ITI ($SD = 3.23$ mm). It is possible to observe clearly the influence of ITI on track geometrical vertical levelling degradation on each rail. An examination of data of rail track roughness calculated over 3 million cycles shows that the SD of vertical profiles grow with the passage of traffic from 0.59 mm and 0.38 mm at $N = 0$ (initial stage) to 1.35 mm and 1.19 mm at 3 million cycles, respectively, for the left and right rails of UT-1 ($SD = 0.48$ mm) in Figure 7.0-5, which finds resonance with Haitham and Murray (2008). The same behaviour is observed for the UT-2 ($SD = 3.23$ mm) in Figure 7.0-6.

On the other hand, the SD of left rail vertical profile for the UT-1 ($SD = 0.48$ mm), for example, increases from 0.59 mm at $N = 0$ (initial stage) to 1.35 mm at 3 million cycles (approximately 2.2 times) in Figure 7.0-5, whereas in Figure 7.0-6 the same left rail for the UT-2 ($SD = 3.23$ mm) rises from 4.60 mm at $N = 0$ (initial stage) to 5.68 mm at 3 million cycles (~ 1.2 times), which indicates that not necessarily a low SD of ITI means that over time after millions of cyclic loadings a track geometrical vertical levelling degradation occurs slower than in a medium SD of ITI track. This is different from a commonly held view that as much higher is the SD of ITI, higher is the rate of increase of roughness with time.

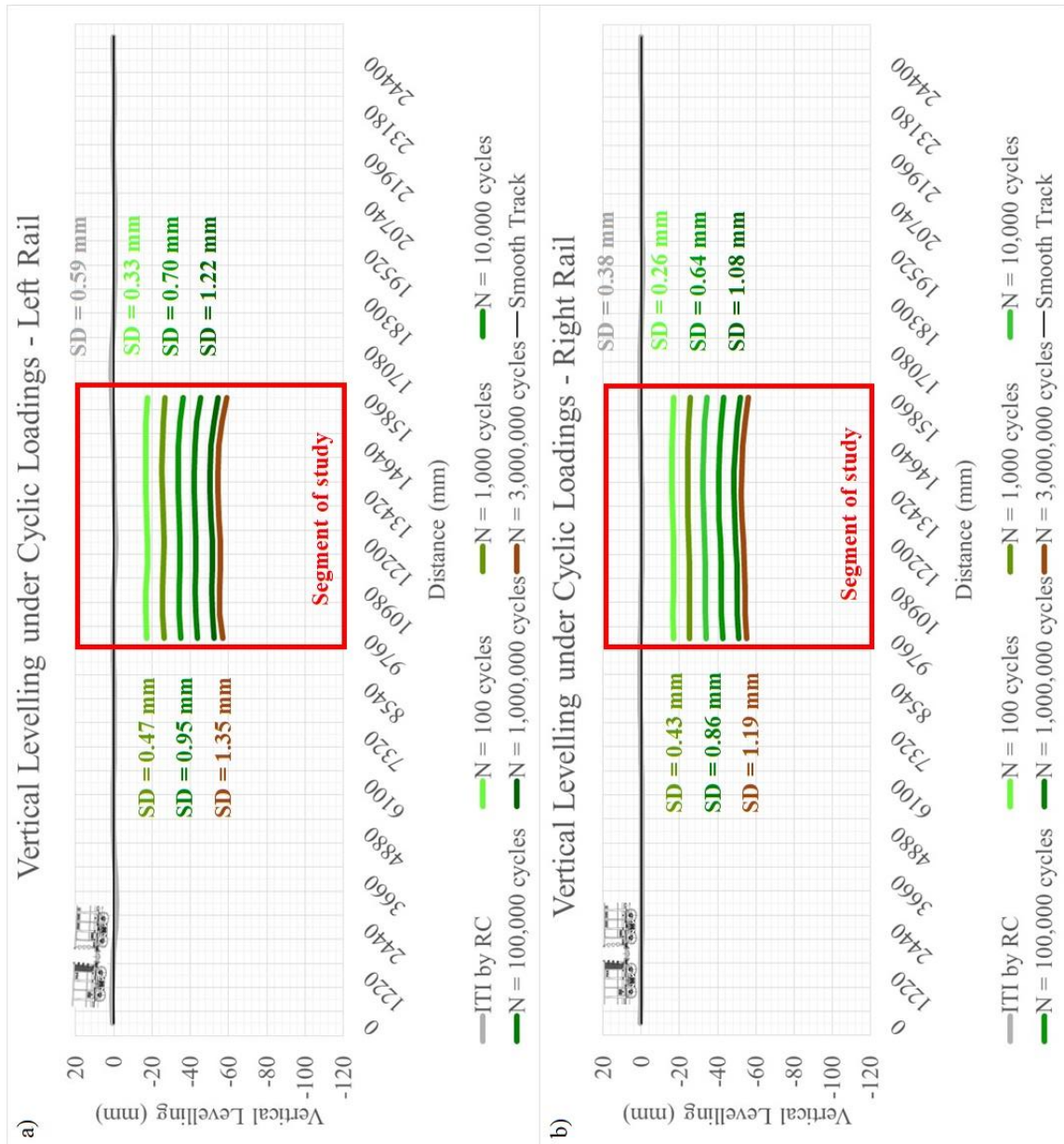


Figure 7.0-5. Track geometrical vertical levelling degradation stages for ITI SD of 0.48 mm (UT-1).

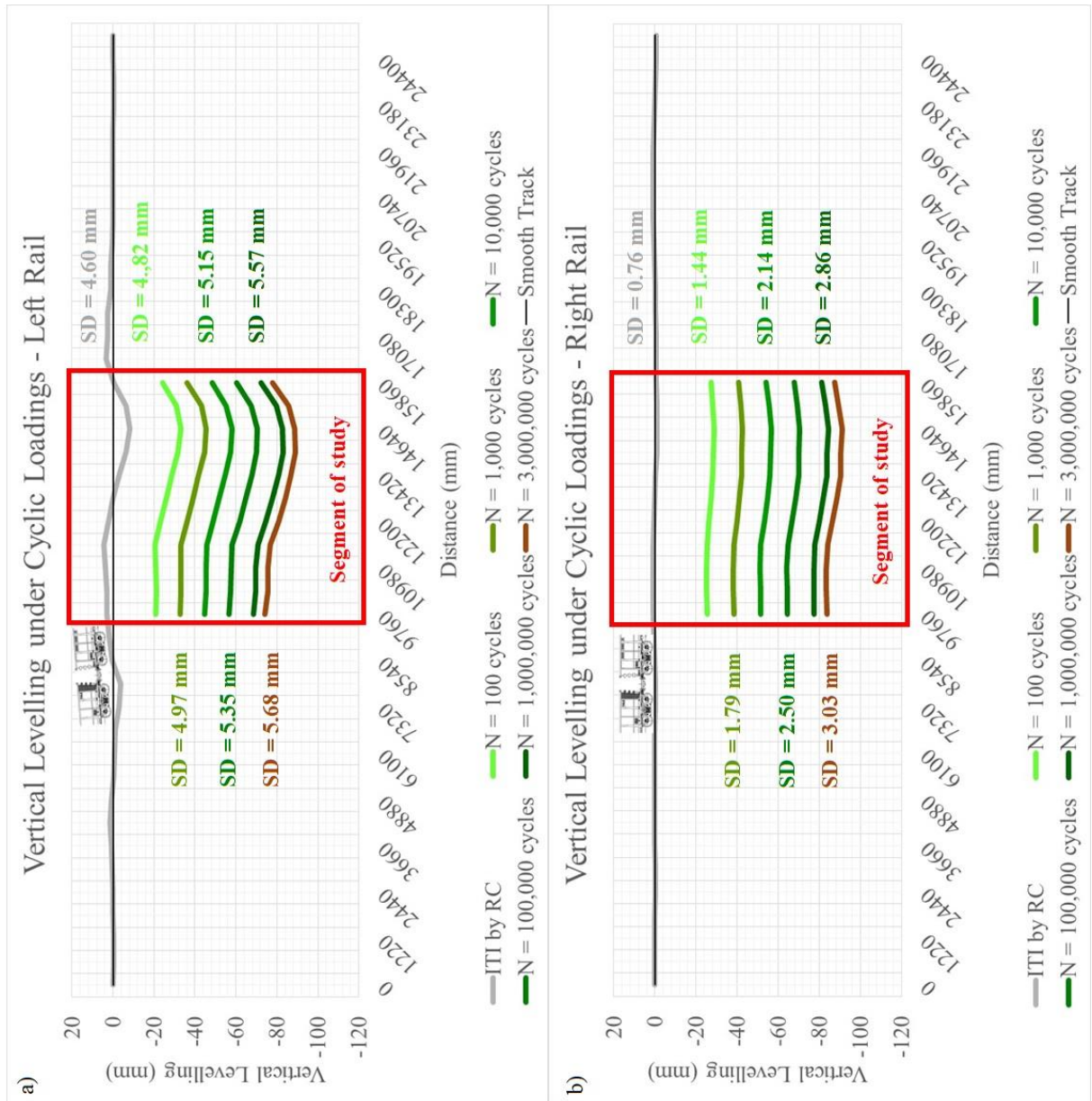


Figure 7.0-6. Track geometrical vertical levelling degradation stages for ITI SD of 3.23 mm (UT-2).

7.4. Parametric Approach

To extend the investigation of the influence of ITI on VLL, different axel loads and train velocities, and those two sets of ITI are applied on FEM under similar track and vehicle parameters as the previous simulation. Figures 7.0-7, 7.0-8, and 7.0-9 show the comparisons of

SD for full track (including both left and right rails in the segment of study) at N = 0 (ITI by RC), N = 100 thousand, N = 1 million, and N = 3 million cycles for 20, 30, and 40-ton axle loads and 60, 70, and 80-km/h train velocities.

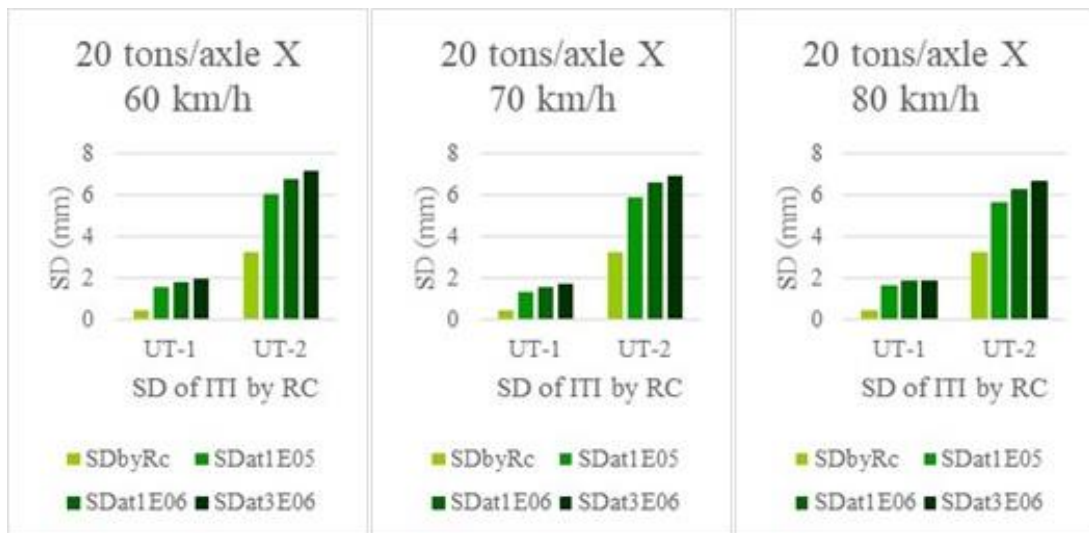


Figure 7.0-7. Comparisons of different SD of vertical profile (UT-1 and UT-2) for full track (including both left and right rails in the segment of study) at N = 0 (ITI by RC), N = 100 thousand, 1 million, and 3 million cycles for 20-tonnes axle load at 60, 70, and 80 km/h train velocity.

For a ballasted railway track dominated by 20-tonnes (a light railway), 30-tonnes (a typical heavy-haul railway), or 40-tonnes (an extreme heavy-haul railway) axle loads, both evolutions of SD of VL (Vertical Levelling) indicate undoubtedly that the ITI influence the behaviour of VLL. The worst SD of VL escalation scenery occurs at uneven track 2 (UT-2) for 20-ton axle load and 60-km/h train velocity, in which the SD of VL increases from 3.23 mm at N = 0, ITI, to approximately 7.2 mm at 3 million cycles. It reflects the natural frequency of the ballasted railway track influenced by the 20-ton axle load and 60-km/h train velocity and by the

track configuration (ITI). For that same 20-ton axle load, the data in Figure 7.0-7 also suggest that a train running at 80 km/h is the best operational configuration for the UT-2 (SD of VL fluctuates from 3.23 mm at N = 0, ITI, to ~6.7 mm at 3M cycles) in terms of minimizing the track geometrical degradation. Whereas, for the uneven track 1 (UT-1), 70-km/h train velocity is the best option (SD of VL increases from 0.48 mm at N = 0, ITI, to ~1.7 mm at 3M cycles). These findings are new and can better explain the effect of ITI on VLL than previous investigations.

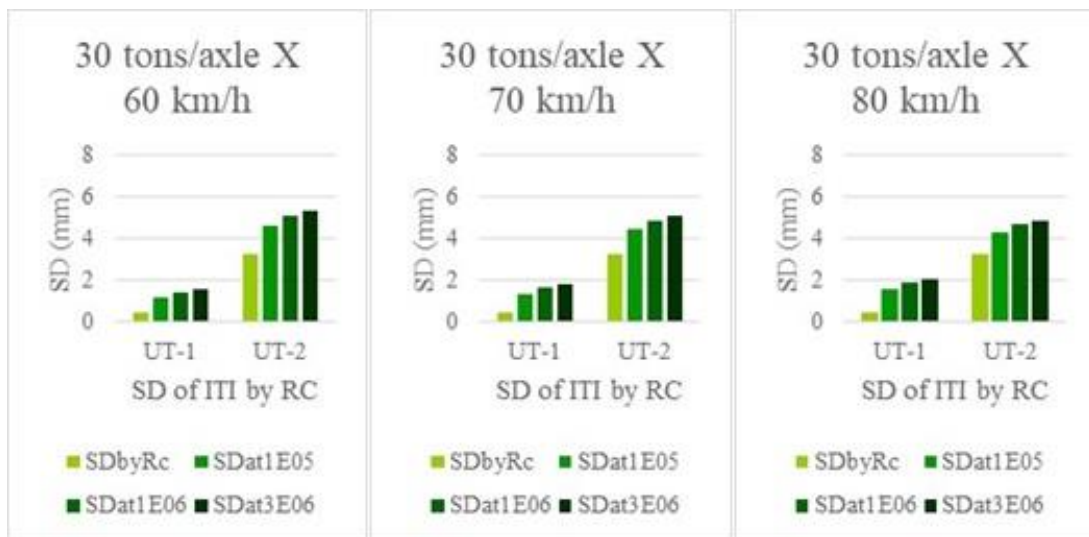


Figure 7.0-8. Comparisons of different SD of vertical profile (UT-1 and UT-2) for full track (including both left and right rails in the segment of study) at N = 0 (ITI by RC), N = 100 thousand, 1 million, and 3 million cycles for 30-tonnes axle load at 60, 70, and 80 km/h train velocity.

Accordingly, if the axle load increases to 30 tonnes, an appropriate operational configuration to minimize the escalation of SD of VL at 3M cycles should be that one in which the train run at 60 km/h at the UT-1 (from 0.48 mm at N = 0, ITI, to ~1.6 mm). In fact, this

configuration is the best one in Figure 7.0-8, and it has intuitively been adopted by some heavy-haul railway companies as described above.

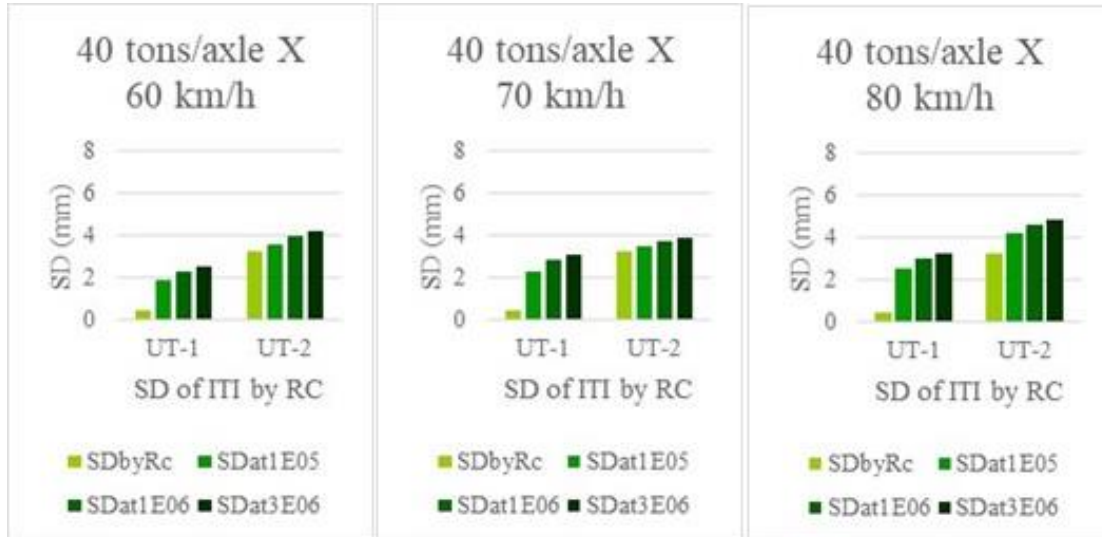


Figure 7.0-9. Comparisons of different SD of vertical profile (UT-1 and UT-2) for full track (including both left and right rails in the segment of study) at N = 0 (ITI by RC), N = 100 thousand, 1 million, and 3 million cycles for 40-tonnes axle load at 60, 70, and 80 km/h train velocity.

On the other hand, if the axle load increases to 40 tonnes, the effect of ITI on the SD of vertical profile over time increases less than those related to 20 and 30-ton axle load for either UT-2 at 60-km/h train velocity (from 3.23 mm at N = 0, ITI, to ~4.2 mm) or UT-2 at 70-km/h train velocity (from 3.23 mm at N = 0, ITI, to ~3.9 mm) at 3M cycles. However, as it can be observed in Figure 7.0-9, one of the best operational configurations for 40-tonnes axle load is to run the train at 60 km/h at a ballasted railway track similarly to UT-1, in which the SD of VL fluctuates from 0.48 mm at N = 0, ITI, to ~2.5 mm at 3M cycles. In turn, if the railway company plans to increase the train velocity to 70 km/h, they should run the train on an uneven track with

the same ITI characteristics of UT-1. In this case, the SD of VL increases from 0.48 mm at $N = 0$, ITI, to ~3,1 mm at 3M cycles, which indicates a reduction of track geometrical degradation rate. Despite this indicating that the axle load and train velocity influence the VLL, the ITI plays a vital role to accelerate it. Other train characteristics can also affect the track geometrical VL degradation such as vehicle suspension stiffness and wheel damping/wheel diameter; however, they have not been discussed in this study. Nevertheless, it is important to highlight that if the ITI increases, the response changes, and it can influence the VLL.

As ITI is usually found in all railways track post-construction or maintenance activities around the World, an acceptable SD of ITI can be defined for a minimum effect on VLL (thresholds). Therefore, these new findings are important not only to prove some rationality adopted by the decision-making of railway infrastructure managers but also to support the development of maintenance guidelines by the track engineers.

7.5. Conclusion

This research presents new insights into the effect of ITI on a ballasted railway track geometrical degradation, particularly in post-construction or maintenance activities. To investigate this phenomenon, a robust numerical-analytical study has been developed and rigorously validated focusing on the track geometrical VLL under cyclic loadings.

For an uneven track, the research not only suggests that there is a clear response of ITI on VLL as described in previous studies, but also innovatively proposes how to numerically capture that effect. For the railway tracks dominated by different axle loads and train velocities, regardless of SD of ITI, the ITI undoubtedly negatively influences the behaviour of VLL, which reflects the natural frequency of the ballasted railway track. The new findings can be useful for

track engineers to predict track geometrical degradation over time under dynamic cyclic loadings.

The research also identifies the worst and the best sceneries of the vertical profile SD evolution in the railway track segment of study. The worst one is related to the operational configuration of a train running at 60 km/h and carrying a load of 20 tons/axle in an uneven track whose SD of vertical profile evolves from 3.23 mm at $N = 0$ (ITI) to 7.2 mm, whereas the best scenery corresponds that one in which a train run at 60 km/h transporting a load of 30 tons/axle in an uneven track whose SD of vertical profile downgrades from 0.48 mm at $N = 0$ (ITI) to 1.5 mm, both sceneries at 3M cycles. The best scenery has currently been adopted by some heavy-haul railways companies around the World.

Even though the insights demonstrate that the axle load and train velocity effects are evident, the ITI condition plays a key role to accelerate further the track geometrical VLL. As the ITI is usually found in all railway track after maintenance activities (there is no smooth track in an actual railway system), an acceptable configuration for it can be defined for a minimum effect on VLL (thresholds). Therefore, given that this novel improved method can accurately predict numerically the effect of ITI on the track geometrical VLL considering different railway operational conditions and configurations, their findings contribute to obtain new insights into track geometrical degradation, and enhance the development of new practical maintenance and construction guidelines to support the maintenance activities in a ballasted railway track.

7.6. Summary

This chapter presents the results and discussion of the application of an original numerical-analytical method as proposed in Chapter 4, Section 4.5, to predict ballasted railway track

geometrical degradation focused on vertical levelling track geometric element in a track with geometry irregularities (uneven track). With an emphasis on the combined degradation of railway track geometry and components, a new numerical-analytical method is proposed for predicting the track geometrical vertical levelling loss (VLL). In contrast to previous studies, this research unprecedentedly considers the influence of initial track irregularities (ITI) on VLL under cyclic loadings, elastic-plastic behaviour, and different operational dynamic conditions.

The nonlinear numerical models are simulated using an explicit finite element (FE) package, and their results are validated by experimental data. The outcomes are iteratively regressed by an analytical logarithmic function that cumulates permanent settlements, which innovatively extends the effect of ITI on VLL in a long-term behaviour. New findings reveal that the worst scenario is related to a train running at 60 km/h and carrying a load of 20 tons/axle in an uneven track whose standard deviation (SD) of vertical profile (VP) evolves from 3.23 mm at $N = 0$ (ITI) to 7.20 mm, whereas the best one corresponds to a train at 60 km/h and 30-ton axle load in an uneven track whose SD of VP downgrades from 0.48 mm to 1.50 mm, both at 3M cycles (or 60 MGT). These finds indicate the importance of considering the ITI for predicting track geometrical VLL under cyclic loadings. Therefore, based on this research, an acceptable condition (thresholds) of ITI can be defined for a minimum effect on VLL, which can support the development of practical maintenance guidelines to extend the railway track service life.

The track with initial track irregularities (vertical levelling) can also contribute greatly to accelerating the VLL in a heavy-haul ballasted railway track. Accordingly, limiting those types of anomalies, which is also a cause of ballast deterioration, is extensive to enhance the track service life. The next chapter will conclude about the ballasted railway track geometrical degradation model approaches and their findings, insights, and limitations for predicting

accurately the dynamic effect/influence of different track conditions (smooth, unsupported-sleeper, and uneven tracks) on downgrading the vertical profile track geometric element. Also, in Chapter 8 (Conclusion and Recommendations), it will be given a special attention in suggesting some improvements to the innovative numerical-analytical method presented in this study not only to extend it to other track geometric elements but also including advanced track and vehicle components properties.

7.7. References

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CONCLUSION AND RECOMMENDATIONS

This chapter presents the overall of this doctoral research findings to support the application of an innovative numerical-approach for predicting track geometrical degradation in a heavy-haul ballasted railway track. Lastly, it presents recommendations to further works in order to improve the outcomes of this doctoral thesis, pointing out the importance of field experiments to calibrate the numerical models.

8.1. Introduction

This doctoral research thesis aims to develop a numerical-analytical approach to predict track geometrical degradation in a heavy-haul ballasted railway track under cyclic loadings to support the understanding of the effect of different operational conditions, track/vehicle parameters, and track conditions on vertical profile loss (VLL). The literature reviews in Chapter 2 and 3 presented and discussed the previous investigations that have been carried out for the last 4 decades, their findings and knowledge gaps. To achieve the aim and the objectives, numerous research activities have been performed at the University of Birmingham through Brazilian National Council for Scientific and Technological Development (CNPq) Project No. 200349/2018-5, while some others have also been developed in collaboration with the University of *São Paulo* (School of Engineering) through European Commission's H2020-RISE Project No. 691135 RISEN (Rail Infrastructure Systems Engineering Network), VALE Mining Company (*Carajás* Railway), and Brazilian National Agency for Land Transports (Superintendence of Railways), in Brazil. The study findings and recommendations for future studies are briefly presented in this chapter.

8.2. Research Findings

As declared in Chapter 1, the accomplishment of the aim is achieved by successfully completing the objectives. The first three objectives permit to identify the existing knowledge gaps regarding to the ballasted railway track geometrical degradation and the influence of different track conditions (smooth, unsupported-sleeper, and uneven tracks) on vertical levelling loss (VLL). The lack of research is then first identified in order to properly conduct the study that should be expanded and had not been done before. Particularly to the critical literature review, it investigates the past and current research regarding to the track geometrical degradation methodologies considering different track conditions, which was adopted for providing a better understanding and supporting the development of an improved numerical-analytical approach.

It is possible to conclude based on the key concepts of heavy-haul ballasted railway systems (1st Objective) that the range of the track and vehicle components parameters can be a challenge to model properly a railway vehicle-track system, specifically to investigate the track geometrical degradation phenomenon.

The mechanism governing the railway track geometrical degradation is a complex process involving several influencing parameters. If a ballasted railway track is recently tamped, relatively large settlements occur due to unequal ballast settlements affecting the track geometric elements, particularly the vertical levelling. If every point of the railway track were to settle by the same amount, no irregularities would develop, then the track is characterized as a smooth track; however, these settlements are often far from uniform due to (2nd Objective) unsupported sleepers (US), and initial track irregularities (ITI), which affecting the track geometrical degradation. When a local vertical profile loss varies along the railway track,

vertical levelling irregularities develop further in a vicious cycle causing an amplification of the dynamic loading of track due to vehicle-track interaction.

Based on an extended critical literature review of the ballasted railway track geometrical degradation models (3rd Objective) considering different track conditions (smooth, unsupported-sleeper, and uneven tracks), it is possible to conclude clearly that there are many research gaps that have never been properly addressed needing to be fully filled to deal with not only the track geometrical degradation process itself but also to support the development of new track maintenance guidelines.

The research is also achieved (4th, 5th and 6th Objectives) using the three methodologies proposed in Chapter 4 whose results are discussed in Chapters 5, 6, and 7. The numerical-analytical approach to predict innovatively the VLL in smooth tracks are presented in Chapter 5. It is important to note that this study applies different railway operational conditions and track/vehicles parameters beyond number of cyclic loadings or million gross tonnes (MGT) to predict dynamically the VLL over time. This methodology can clearly identify the best track-vehicle parameters to minimize the VLL. However, that methodology has limitation as it considers a ballasted railway as a perfect track, what it is not true in a real ballasted railway track. In order to overcome this limitation, the effect or influence of different track condition, mapped in Chapter 2 and 3 as, respectively, unsupported-sleeper (Chapter 6) and uneven tracks (Chapter 7), are included originality to improve the nonlinear numerical-analytical approached initially proposed in Chapter 5. These approaches consider nonlinear properties of those track conditions; therefore, the outcomes provide higher accuracy than the method proposed in Chapter 5 (smooth tracks).

8.2.1. Vertical levelling loss in smooth tracks

The conclusions that can be drawn from the application of the innovative numerical-analytical approach to predict the VLL in a heavy-haul ballasted railway track are:

- The VLL can be accurately represented by a linear degradation with the logarithm of the number of cyclic loadings including depended variables related to operational conditions and track/vehicle parameters as coefficients to build graphics and abacus.
- It is possible to extent the VLL prediction to evaluate its long-term behaviour following its regression function, which is usually applied in field and laboratory experiments.
- The innovative numerical-analytical approach can very well predict the VLL long-term performance considering not only the number of cycles or MGT but also the different dynamic conditions.
- The innovative numerical-analytical approach can support the development of a specification to proceed the investigation of track geometrical degradation.
- The innovative numerical-analytical approach can support more complex analysis of track geometry elements with a minimal need of carrying out expensive field experiments.

8.2.2. Effect of unsupported-sleeper track on vertical levelling loss

Additionally, to those of smooth tracks, the conclusions that can be summarized from the effect of unsupported-sleeper track on VLL in a heavy-haul ballasted railway track are:

- There is a noticeable influence of US on VLL, however, it is reduced as much as the axle load increases meaning that the dynamic wheel-rail contact force for a heavy haul railway can lead the whole ballasted track settlement over time.

- For a light railway, if the vertical rail displacement is closer to the gap beneath the sleeper, the increase of impact loading is more influenced by the US conditions.
- The axle load effect is more evident on VLL in unsupported-sleeper track. Nonetheless, the US condition plays a significant role to contribute further on track geometrical VLL.
- The US condition can usually be observed in railway tracks implying that an acceptable configuration must be specified for a minimum effect on VLL.
- The innovative improved numerical-analytical approach can accurately predict the effect of US on the track geometrical VLL considering different railway operational conditions (and configurations).
- The innovative improved numerical-analytical approach can be applied to enhance the development of new practical maintenance and construction guidelines to minimize the effect of US on VLL.

8.2.3. Influence of uneven tracks on vertical levelling loss

Additionally, to those smooth tracks, the conclusions that can be summarized from the influence of uneven tracks on VLL in a heavy-haul ballasted railway track are:

- The research suggests that there is a clear response of initial track irregularities (ITI) on VLL as described in previous studies.
- Innovatively the study numerically captures the influence of ITI on VLL in a heavy-haul ballasted railway track.
- For heavy-haul ballasted railway tracks dominated by different axle loads and train velocities, regardless of Standard Deviation (SD) of ITI, the ITI negatively influences the behaviour of VLL.

- The influence of ITI on VLL reflects mainly the natural frequency of the ballasted railway track.
- The new findings can be useful for track engineers to predict track geometrical degradation over time under dynamic cyclic loadings.
- The research identifies the worst scenery (combination of operational conditions, track/vehicle parameters, and sets of ITI) is related to the operational configuration of a train running at 60 km/h and carrying a load of 20 tons/axle in an uneven track whose SD of vertical profile evolves from 3.23 mm at $N = 0$ (ITI) to 7.2 mm, at 3M cycles.
- The best scenery is related to the operational configuration of a train running at 60 km/h transporting a load of 30 tons/axle in an uneven track whose SD of vertical profile downgrades from 0.48 mm at $N = 0$ (ITI) to 1.5 mm, at 3M cycles.
- The configuration above (best scenery) has intuitively been adopted by the *Carajás* Railway, a heavy-haul railway company in Brazil.
- The axle load and train velocity influences are evident; however, the ITI condition plays a key role to accelerate further the track geometrical VLL.
- The ITI is usually found in all railway track after maintenance activities, which indicates that an acceptable configuration for it can be defined for a minimum effect on VLL.
- The original improved numerical-analytical approach can accurately predict the influence of ITI on VLL considering different railway operational conditions, track/vehicle parameters and ITI configurations.
- The innovative improved numerical-analytical approach can also be used to enhance the development of new practical maintenance and construction guidelines to support the maintenance activities in a heavy-haul ballasted railway track.

8.3. Recommendations for Further Studies

One of the most important characteristics of heavy-haul ballasted railway system that FEM (Finite Element Method) model is not able to simulate are the ballast fouling, and the dropped and migration of fines from iron ore or coal wagons into the railway ballast. There are important characteristics in that kind of railway system that need further research. Despite the numerous findings reported in this doctoral research thesis, future research is needed to further extend the modelling and performance into an even more real-life heavy-haul railway system. The results of this research have increased the need for future studies as follows:

- Further research should focus on a nonlinear elastic-plastic behavior not only to the railway ballast, but also to sub ballast and subgrade as this aspect is crucial when the formation is constructed over a soft soil, which can experience large cumulative deformation.
- Even considering elastic-plastic behaviour parameters of ballast and infrastructure components, it is known that those parameters is not constant under dynamic cyclic loadings, therefore a more accurate model requires as input new curves (law) of material behaviour, especially to railway ballast.
- Field experiments under cyclic loadings and different track conditions (unsupported-sleepers and uneven tracks) should be carried out to validate/calibrate the models as currently data are limited around the World and consider basically monotonic loading and elastic behaviour of materials.
- Extend the studies to other track geometric elements such as lateral alignment, cant and twist, on curve segments. In this case, track lateral resistance must be considered to properly resist the effect of centrifugal forces in this kind of segment (track curve). It is

recommended that a curve track segment be modelled considering both the transition and the circular curves to reduce the transient forces in a numerical analysis.

APPENDIX

APPENDIX A

Table A.1. Summary of the different strategies adopted to carry out the literature reviews regarding railway track components deterioration and geometrical degradation.

Author(s)	Title	Description	Gap(s)
Dahlberg (2001)	A Survey on track geometry degradation modeling	Track settlements in function of number of cyclic loadings	Not describe models that consider the influence of track geometric irregularities, the vehicle parameters, and the plastic deformation of materials
Berawi (2013)	Improving railway track maintenance using Power Spectral Density (PSD)	Track geometrical degradation based on two different point of views: structural (e.g., ballast settlements), and geometrical (e.g.: vertical levelling). Both viewpoints in	Not describe models that consider the railway operational condition (e.g., axle load, and train velocity), and the vehicle parameters

		function of number of cyclic loadings	
Ngamkhanong et al. (2017)	A review on modelling and monitoring of railway ballast	Track deflection based on elastic behaviour of railway ballast	Not describe models that consider the railway operational condition (e.g., train velocity), the vehicle parameters, and the plastic behaviour of material (e.g., railway ballast)
Ngamkhanong et al. (2018)	State-of-the-art review of railway track resilience monitoring	Rail buckling, floodings, and washing-away ballast by floods (effects of climate changes)	Not describe models that consider the railway operational condition (e.g., train velocity), the vehicle parameters, and the plastic behaviour of material (e.g., railway ballast)
Soleimanmeigouni et al. (2018)	Track geometry degradation and	Track geometrical degradation based on	Not describe models that consider the

	<p>maintenance modelling: a review</p>	<p>different approaches: mechanistic, statistical, and mechanical-empirical</p>	<p>railway operational condition (e.g., axle load, and train velocity), the vehicle parameters, and the plastic behaviour of material</p>
<p>Elkhoury et al. (2018)</p>	<p>Degradation prediction of rail tracks: a review of the existing literature</p>	<p>Track geometrical degradation based on different approaches: mechanistic, statistical, mechanical-empirical, and artificial intelligence</p>	<p>Not describe models that consider the railway operational condition (e.g., axle load, and train velocity), the vehicle parameters, and the plastic behaviour of material</p>
<p>Higgins and Liu (2018)</p>	<p>Modeling of track geometry degradation and decisions on safety and maintenance:</p>	<p>Track geometrical degradation models based on statistical (empirical) approach</p>	<p>Not describe models that consider the railway operational condition (e.g., axle load, and train velocity), the</p>

	A literature review and likely future research direction		vehicle parameters, and the plastic behaviour of material
Melo et al. 2020	Methods to monitor and evaluate the deterioration of track and its components in a railway in-service: a systemic review	Track geometrical degradation based on different tactics: model type (statistic, mechanistic, or empiric-mechanistic), and kind of approach (observable, experimental, numerical, and hybrid numerical-experimental or numerical-analytical)	Not describe models that consider the vehicle parameters

Table B.1. Summary of different railway ballast settlement models in smooth tracks obtained from different literature reviews related to track geometrical degradation (Dahlberg 2001, Thom and Oakley 2006, and Grossoni et al. 2019).

Author(s)	Title	Description	Gap(s)
Shenton (1978)	Deformation of railway ballast under repeated loading conditions	Function of the initial ballast settlement and the logarithmic of the number of cyclic loadings	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, the track components parameters, and the track condition (e.g., track geometric irregularities)
Steward and Selig (1984)	Correlation of concrete tie track performance in revenue service and at the facility for	Function of the initial ballast settlement and the logarithmic of the number of cyclic loadings	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, the track components parameters, and the track condition (e.g.,

	accelerated service testing		track geometric irregularities)
Jeffs and Marich (1987)	Ballast characteristics in the laboratory	Function of the Napierian logarithmic of the number of cyclic loadings	Not consider different railway operational conditions, the vehicle parameters, and the track components parameters
Selig and Waters (1994)	Track Geotechnology and Substructure Management	Power function of the number of cyclic loadings	Not consider different railway operational conditions, the vehicle parameters, the track components parameters, and the track condition
Guerin (1996)	Numerical and Experimental Approach of Ballast Component of Railway Track	Function of incremental deformation based on the number of load cycles	Not consider different railway operational conditions, the vehicle parameters, the track components parameters, and the track condition
Sato (1995)	Japanese studies on deterioration of ballasted track	Function of proportional influences of average train velocity, passaged	Not consider the vehicle parameters, the track components parameters, and the track condition

		tonnage (traffic volume), rail structure (jointed rail or CWR), structural track factor, and subgrade factor	
Frohling (1998)	Low frequency dynamic vehicle-track interaction: modelling and simulation	Function of the Napierian logarithmic of the number of cyclic loadings, and the ration of dynamic and static loads	Not consider the vehicle parameters, and the track components parameters
Indraratna and Salim (2007)	Deformation and degradation mechanics of recycled ballast stabilised with geosynthetics	Function of the initial ballast settlement, and the Power function of the number of cyclic loadings	Not consider different railway operational conditions, the vehicle parameters, the track components parameters, and the track condition
Cuelar (2011)	Short and long-term behaviour of high-speed lines as determined in 1:1 scale	Function of the initial ballast settlement and the Power function of	Not consider the railway operational conditions, the vehicle parameters, the track components parameters, and the track condition

	laboratory tests	the number of cyclic loadings	
Indraratna et al. (2012)	Deformation of coal fouled ballast stabilized with geogrid under cyclic load	Function of the initial ballast settlement and the 2 nd order of Napierian logarithmic of the number of cyclic loadings	Not consider the railway operational conditions, the vehicle parameters, the track components parameters, and the track condition
Indraratna and Nimballkar (2013)	Stress-strain degradation response of railway ballast stabilized with geosynthetics	Function of the initial ballast settlement and the 2 nd order of Napierian logarithmic of the number of cyclic loadings	Not consider the railway operational conditions, the vehicle parameters, the track components parameters, and the track condition
Estaire and Vicente (2017)	CEDEX Track Box as an experimental tool to test railway tracks at 1:1 scale	Power function of the number of cyclic loadings	Not consider the railway operational conditions, the vehicle parameters, the track components parameters, and the track condition

Table C.1. Summary of techniques proposed by each track geometrical degradation method to predict the effect of US on VLL (Melo et al. 2023a).

Author(s)	Title	Description	Gap(s)
Grassie and Cox (1984)	The dynamic response of railway track with unsupported sleepers	Examined experimentally the effect of traditional US on dynamic wheel-rail contact force	Not consider a long-term performance, and plastic properties of material (e.g., railway ballast)
Augustin et al. (2003)	Numerical model and laboratory tests on settlement of ballast track	Investigated numerically and experimentally the influence of inaccurately positioned sleepers on track settlement under cyclic loadings	Not distinguish the influence of badly placed sleepers on the evolution of track geometrical vertical deformation.
SUPERTRACK (2005)	Sustained Performance of Railway Tracks	Performed a numerical modelling of railway track introducing gaps of 0.5 mm and 1 mm	Not consider a long-term performance

		under three cyclic loadings and ballast plastic behaviour	
Lundqvist and Dahlberg (2005)	Load impact on railway track due to unsupported sleeper	Performed a numerical modelling of railway track introducing US gaps under monotonic loading and elastic ballast behavior	Not consider a long-term performance, and plastic properties of material (e.g., railway ballast)
Zhang et al. (2008)	Effect of unsupported sleepers on wheel/rail normal load	Studied the effect of US on the normal load of wheel-rail through a numerical simulation	Not consider a long-term performance, and plastic properties of material (e.g., railway ballast)
Bezin et al. (2009)	An investigation of sleeper voids using a flexible track model integrated with railway multi-body dynamics	Studied the cant deficiency effect of rail on the railway tracks with US by using numerical modelling	Not consider a long-term performance, and plastic properties of material (e.g., railway ballast)
Zakeri et al. (2015)	Influence of unsupported and partially	Performed numerical simulations to identify the magnitude of impact	Not consider a long-term performance, and plastic properties of

	supported sleepers on dynamic responses of train–track interaction	load with different US gap ranges	material (e.g., railway ballast)
Zhu et al. (2008)	On the effect of unsupported sleepers on the dynamic behaviour of a railway track	Investigated the effect of traditional US on the track dynamic characteristics by experiments	Not consider a long- term performance, and plastic properties of material (e.g., railway ballast)
Ienaga et al. (2016)	Numerical and experimental study on contact force fluctuation between wheel and rail considering rail flexibility and track conditions	Carried out numerical simulation and experiments under low- speed range to investigate the effects of traditional US	Not consider a long- term performance, and plastic properties of material (e.g., railway ballast)
Sadeghi et al. (2018)	Effect of unsupported sleepers on rail	Researched the response of traditional US using an improved 3D	Not consider a long- term performance, and plastic properties of

	track dynamic behaviour	numerical model and experiments	material (e.g., railway ballast)
Sysyn et al. (2020)	Experimental investigation of the dynamic behavior of railway track with sleeper voids	Carried out experimental and numerical investigation to study the dynamic interaction between the wheel and the rail with US	Not consider a long-term performance, and plastic properties of material (e.g., railway ballast)
Azizi et al. (2020)	Investigation on Effect of Train Speed in Displacement of Railway Ballasted Track with Unsupported Sleepers	Investigated numerically and experimentally the response of train velocity in displacement of a ballasted railway track with traditional US	Not consider a long-term performance, and plastic properties of material (e.g., railway ballast)
Sresakoolchai and Kaewunruen (2022)	Prognostics of unsupported railway sleepers and their severity diagnostics using machine learning	Proposed an innovative prognostic to detect and identify severities of US using machine learning based on a verified numerical simulation	Not consider a long-term performance, and plastic properties of material (e.g., railway ballast)

		with existing field measurements	
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APPENDIX

APPENDIX D

Table D.1. Summary of the strategies adopted by each track geometrical degradation method identified that predicted the influence of initial track irregularities on VLL (Melo et al. 2023b).

Author(s)	Title	Description	Gap(s)
Partington (1979)	TM-TS-097: Track Deterioration Study – Results of the Track Laboratory Experiments	Investigated experimentally in laboratory the influence of ITI on VLL	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, and track components parameters
Suiker and Borst (2003)	A numerical model for the cyclic deterioration of railway tracks	Performed a numerical modelling of railway track introducing dynamic amplification factors to investigate long- term track geometrical degradation	Not consider the vehicle and track parameters, and simplify the long-term performance

Augustin et al. (2003)	Numerical model and laboratory tests on settlement of ballast track	Also studied the effect of great initial height variance of ITI on VLL	Not distinguish the influence of track irregularities on evolution of track geometrical vertical deformation
Takemiya and Bian (2005)	Substructure simulation of inhomogeneous track and layered ground dynamic interaction under train passage	Studied distinct characteristics of layered subgrade and moving axle loads	Not consider the vehicle parameters, and track superstructure components parameters
Hawari and Murray (2008)	Deterioration of railway track on heavy haul lines	Investigated experimentally in three sites the relationship between the SD of roughness of a railway track segment and the rate at which the vertical profile geometry of	Not consider the vehicle parameters, and track components parameters

		that track segment deteriorated	
Chang et al. (2010)	A multi-stage linear prediction model for the irregularity of the longitudinal level over unit railway sections	Performed field experiments considering total passing tonnage	Not consider the train velocities, the vehicle parameters, and track components parameters
Faiz (2010)	An empirical rail track degradation model based on predictive analysis of rail profile and track geometry	Investigated the effect of univariate and multivariate correlation analysis of track irregularities on the track dynamic characteristics	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, and track components parameters
Choi et al. (2012)	The influence of track irregularities on the running behavior of high-speed trains	Conducted a numerical simulation research to investigate the influence of track irregularities with various wavelengths and amplitudes	Not consider the track components parameters, and the long-term performance

Berawi (2013)	Improving railway track maintenance using power spectral density (PSD)	Studied the influence of track irregularities based on PSD	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, and track components parameters
Guler (2014)	Prediction of railway track geometry deterioration using artificial neural networks: a case study for Turkish state railways	Studied the effect of track roughness modelling the railway track geometrical degradation with ANN	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, and track components parameters
Choi (2014)	Qualitative analysis for dynamic behavior of railway ballasted track	Evaluated theoretically and experimentally the dynamic features of a ballast track	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, and the long-term performance

<p>Naeimi et al. (2015)</p>	<p>Dynamic response of sleepers in a track with uneven rail irregularities using a 3D vehicle–track model with sleeper beams</p>	<p>Applied numerical modelling to investigate the influence of irregular rail cases on the dynamic responses of consecutive sleepers</p>	<p>Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, and the long-term performance</p>
<p>Shen et al. (2015)</p>	<p>Analysis of Effect Parameters of Track Settlement in Heavy Haul Railways</p>	<p>Investigated the effect of vertical track irregularities on ballast settlement under few cyclic loadings</p>	<p>Not consider the vehicle and track parameters, and the long-term performance</p>
<p>Nguyen et al. (2016)</p>	<p>A computational procedure for prediction of ballasted track profile degradation</p>	<p>Studied numerically based on an empirical ballast settlement law the effect of track geometry defects under railway traffic cyclic</p>	<p>Not consider the vehicle and track parameters, and simplify the long-term performance</p>

	under railway traffic loading		
Soleimanmeigouni et al. (2017)	Modelling the evolution of ballasted railway track geometry by a two-level piecewise model	Proposed a two-level framework to model the evolution of track geometry degradation over a spatial and temporal space using a simple linear model	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, and the track parameters
Nielsen and Li (2018)	Railway track geometry degradation due to differential settlement of ballast/subgrade – numerical prediction by an iterative procedure	Carried out a numerical investigation to study the dynamic interaction between the wheel and the rail with longitudinal level and empirical settlement of ballast/subgrade	Not consider different railway operational conditions (e.g., axle load, and train velocity), the vehicle parameters, the track parameters, the interaction between different regions of the track substructure
Guo and Zhai (2018)	Long-term prediction of track geometry degradation in high-speed	Carried out numerical simulation based on an empirical power model for settlement prediction to	Not consider the vehicle track parameters, and simplify the long-term performance

	vehicle– ballastless track system due to differential subgrade settlement	investigate the effect of track subgrade settlement with a regular operation pattern	
De Miguel et al. (2018)	Numerical simulation of track settlements based on an iterative integrated approach	Researched the response of track geometry irregularities by implementing an empirical settlement law and MBS	Simplify the long-term performance
Grossoni et al. (2019)	The role of track stiffness and its spatial variability on long-term track quality deterioration	Investigated analytically the role of track stiffness and its spatial variability through a set of computational experiments estimating the track geometry degradation rates	Not consider the vehicle parameters, and simplify the long-term performance

Soleimanmeigounia et al. (2020)	Prediction of railway track geometry defects: a case study	Developed a data-driven analytical approach considering the occurrence of shock events	Not consider the vehicle and track parameters
Bednarek (2021)	Full-scale field experimental investigation on the intended irregularity of CWR (Continuous joint or Welded Rail) track in vertical plane	Carried out a full-scale field experimental investigation and simulated the influence of short track geometry irregularities statically and with elastic parameters of the track components	Not consider the vehicle parameters, the plastic behavior of track components (e.g., railway ballast), the long-term performance
Grossoni et al. (2021)	Modelling railway ballasted track settlement in vehicle-track interaction analysis	Suggested a semi-analytical approach based on the known behavior of granular materials under cyclic loadings	Not consider the vehicle parameters, and simplify the long-term performance

Kosukegawa et al. (2023)	Spatiotemporal forecasting of vertical track alignment with exogenous factors	Proposed a method to forecast the vertical profile from track roughness using a convolutional long short-term memory	Not consider the vehicle parameters
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