Influence of the train speed in the performance of a ballastless track in a transition zone

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Abstract. The ballastless track is the most popular railway system nowadays. This is due to the associated reduced maintenance costs and operations. Indeed, in recent years there has been a shift from the ballasted track to the ballastless track, mostly in Asia, but also in Europe. Considering both railway structures, their performance in transition zones is a major concern of the Railway Infrastructure Managers. These areas are characterized by an abrupt change in the track stiffness, which leads to the development of differential settlements and the growth of dips and bumps, accelerating the degradation of the track. Thus, it is crucial to have a methodology able to accurately predict the performance of the ballastless tracks in transition zones, mostly in the scope of high-speed lines. This work presents a detailed analysis regarding the evaluation of the performance of a ballastless track in an embankment-tunnel transition zone considering the influence of the train speed. In this analysis six different train speeds were adopted: 220 km/h, 360 km/h, 500 km/h, and 600 km/h. Moreover, the influence of the critical speed is also evaluated. The adopted and developed methodology is a novel and hybrid approach that allows including short-term and long-term performance, through the development of a powerful 3D model combined with the implementation of a calibrated empirical permanent deformation model.

Keywords: ballastless track, high-speed lines, transition zones.

1 Introduction

Transition zones in railway networks are characterized by abrupt changes in track stiffness, leading to differential settlements and the formation of dips and bumps (Indraratna, Babar Sajjad [1, Ramos, Gomes Correia [2]). These zones are major sources of issues, significantly impacting maintenance operations and costs (Frohling, Scheffel [3, Hunt [4, Nicks [5]). Differential settlements increase dynamic wheel loads and amplify vertical train-track interactions, resulting in noise, vibration, poor ride comfort, a higher risk of derailment, hanging sleepers, permanent rail deformation, ballast penetration into the subgrade, and cracking of concrete sleepers or slabs (Paixão, Fortunato [6, Banimahd, Woodward [7, Grossoni, Hawksbee [8]).

The causes of these issues in transition zones include changes from ballasted to ballastless tracks, transitions from embankments to tunnels or bridges, and the presence of hydraulic underpasses or box culverts. Despite the high initial investment, ballastless tracks have gained popularity in high-speed rail lines due to their reduced maintenance operations and costs (Matias and Ferreira [9]). However, it is important to ensure their optimal performance regarding, for example, the deformation limits, particularly concerning long-term deformations, necessitating advanced numerical modeling to accurately predict permanent settlements.

This study assesses the short and long-term performance of a ballastless track within a transition zone, with a focus on the influence of train speed, including critical speeds. Accelerated degradation of geomaterials due to higher train speeds leads to excessive settlements, posing significant challenges in transition zones (Gu, Zhao [10]). Specifically, this study examines a transition between an embankment and a tunnel. The modeling incorporates vehicle-track and super-substructure interactions using a hybrid approach to evaluate track performance at various train speeds: 220 km/h, 360 km/h, 500 km/h, and 600 km/h. Short-term performance is analyzed with a powerful 3D FEM model developed in ANSYS, while permanent deformation is evaluated using a calibrated empirical model designed to simulate track degradation.

2 Numerical model

The numerical model represents a ballastless track consisting of rails, railpads, a concrete slab, a hydraulically bonded layer (HBL), and a substructure that includes the frost protection layer (FPL) and subgrade, as depicted in Figure 1. The concrete slab has a thickness of 0.2 m, the HBL is 0.3 m thick, and the FPL measures 0.4 m. The subgrade has a thickness of 10.5 m. Material characteristics can be found in Ramos, Gomes Correia [2], with key properties listed in Table 1, based on prior calibration work by the same authors (Ramos, Gomes Correia [11]).

Damping coefficients were determined using the Rayleigh damping matrix, with additional details available in Ramos, Gomes Correia [2]. A frequency range of 5 Hz to 200 Hz was adopted to ensure accurate track response.

As shown in Figure 1, the numerical model spans 53.1 meters, covering both the 31.65-meter embankment and the 21.25-meter tunnel. To enhance computational efficiency, symmetric boundary conditions were employed. The distance between the symmetry plane and the vertical boundary is 6 meters, with x = 0 meters marking the transition point between the embankment and the tunnel.

The analysis focuses on the passage of the Portuguese Alfa Pendular train at varying speeds of 220 km/h, 360 km/h, 500 km/h, and 600 km/h. Detailed train and model properties can be found in Ramos, Gomes Correia [2]. The train components include bogies, primary suspension, mass, and wheelset axles, incorporating Hertzian stiffness to replicate the vehicle-track interaction.

A constant load of 67.5 kN (135/2) was applied. To simulate both short-term and long-term track responses, the passage of the initial four bogies was modeled. Viscous dampers were used to avoid spurious reflections and attenuate waves impinging on the vertical boundaries, placed in the FPL and subgrade materials using the Lysmer formulation.

The materials were modeled with 8-node solid elements using linear elastic models. Contact elements were implemented between the train and track to simulate their interaction, and between the HBL and FPL to simulate the "detachment" between these elements. The dynamic analysis was performed using ANSYS software with the Newmark-Raphson method, employing a time step of 0.002 seconds.

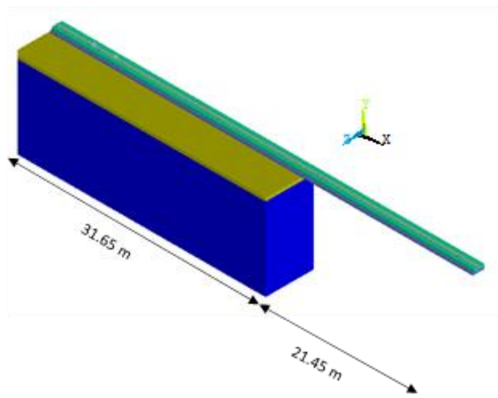


Figure 1. 3D Numerical model

Table 1. Properties of the materials (adapted from Ramos, Gomes Correia [2])

Material	Properties		
Rail (BS113A)	$E=200 \times 10^9$ Pa	$\gamma=7850$ kg/m^3	$\nu=0.3$
Railpad	$K=1800\times10^6$ N/m E=k× thickness /area	$\gamma=1000$ kg/m^3	$\nu=0.3$
Steel plate	$E=210\times10^9$ Pa	$\gamma=7850$ kg/m^3	$\nu=0.3$

EPDM (ethylene propylene diene monomer)	K=40×10^6 N/m E=k× thickness /area	γ=1200 kg/m^3	ν=0.0
Cement grout	E=25×10^9 Pa	γ=2000 kg/m^3	ν=0.25
Concrete slab	E=40×10^9 Pa	γ=2500 kg/m^3	ν=0.25
HBL	E=15×10^9 Pa	γ=2400 kg/m^3	ν=0.25
FPL	E=445.5×10^6 Pa	γ=2141 kg/m^3	ν=0.35
Subgrade	E=214.5×10^6 Pa	γ=2091 kg/m3	ν=0.35

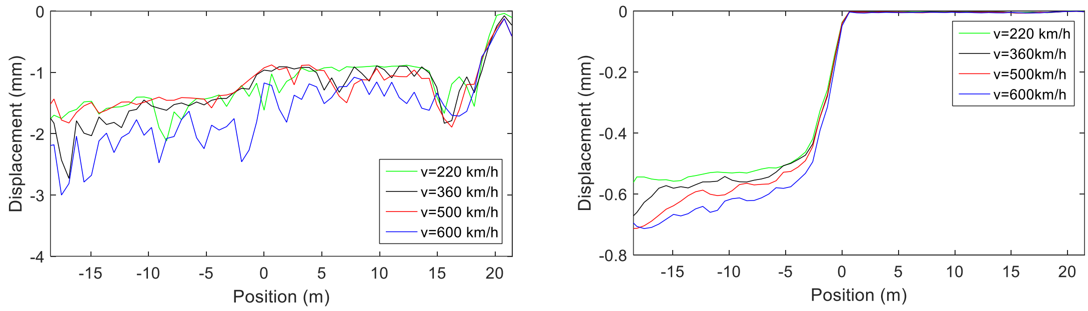
3 Results

The objective of this study is to evaluate the impact of train speed on the dynamic response of a ballastless track within a transition zone. To achieve this, different simulations were conducted at four distinct train speeds: 220 km/h, 360 km/h, 500 km/h, and 600 km/h. This wide range of speeds was selected to assess the performance of a high-speed railway line within a transition zone comprehensively. The highest speed, 600 km/h, was specifically chosen to investigate the influence of the critical speed on the rail track's behavior, as substantial amplifications of the track's response are expected at this speed.

3.1 Short-term behaviour

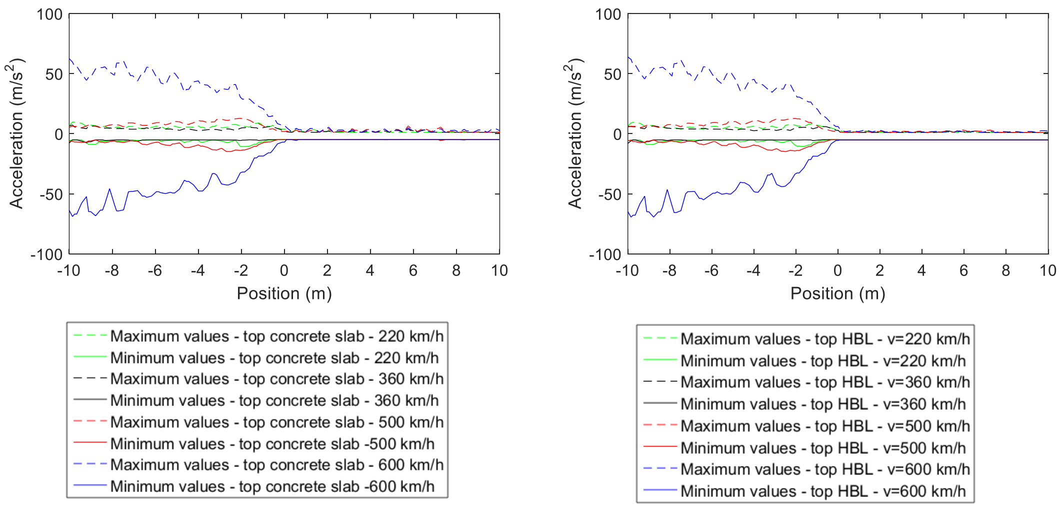
The short-term performance assessment focuses on analyzing the displacements and accelerations induced in the different track components. Maximum displacements at the top of the rail and concrete slab were obtained in alignment under the rail (Figure 2). The results indicate that displacements increase with higher train speeds. Specifically, at a train speed of 600 km/h, there is a significant amplification in both the magnitude and variation of rail displacements. Similarly, displacements in the concrete slab also scale proportionally with train speed, particularly in sections far from the transition.

In addition to displacement analysis, vertical accelerations at the top of the concrete slab and HBL were measured. These elements are crucial for maintaining track continuity. The results show the maximum and minimum vertical acceleration values along the track under the load alignment. A significant increase in acceleration corresponds to higher train speeds, especially in the concrete slab and HBL, particularly before the transition zone (x = 0 m) at 600 km/h. At this speed, acceleration exceeds acceptable thresholds, typically set below 10 m/s². For the other speeds, the results fall within acceptable ranges. As expected, the results also show a decline in vertical acceleration along the transition zone.



a) b)

Figure 2. Maximum displacement induced in the top of the rail (a) and concrete slab (b)



a) b)

Figure 3. Vertical accelerations induced in the concrete slab (a) and HBL (b)

3.2 Long-term behaviour

In this analysis, the prediction of the permanent deformation was obtained at the FPL and subgrade, which are the geomaterials. The permanent deformation is determined by applying the empirical model developed by Chen, Chen [12]:

$$\varepsilon_1^p(N) = \varepsilon_1^{p0}\left[1 - e^{-BN}\right]\left(\frac{\sqrt{{p_{am}}^2+{q_{am}}^2}}{p_a}\right)^a \cdot \frac{1}{m\left(1+\frac{p_{ini}}{p_{am}}\right)+\frac{s}{p_{am}}-\frac{(q_{ini}+q_{am})}{p_{am}}} \quad (1)$$

where the parameters ε_1^{p0}, B and a are the material's constants of the model, m and s are defined by the yielding criterion $q=s+m \cdot p$, N is the number of loading cycles, p_{ini} and q_{ini} are the initial stress state and p_{am} and q_{am} are the stress levels induced in the subgrade during the passage of the train.

The constants used to characterize the empirical permanent deformation model were obtained in a previous study by Ramos, Gomes Correia [11]. In this context, each cycle (N) corresponds to the passage of one of the 24 axles of the Alfa Pendular train.

This methodology involves developing a robust 3D numerical model of the vehicle-track system using ANSYS software. The numerical results provide the stress in the subgrade and FPL in all directions and for all elements and nodes. These stress values are then exported to MATLAB to predict permanent deformation based on the selected empirical permanent deformation model. In this analysis, each curve of the permanent deformation corresponds to 1 million load cycles.

Although permanent deformation is a critical factor, the results are analyzed in terms of cumulative permanent settlements to determine the overall magnitude of the track's settlement:

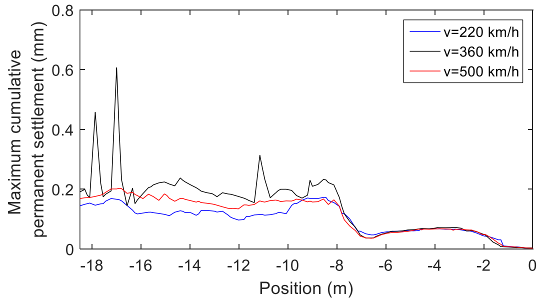
$$\delta = \sum_{i=1}^{n} \varepsilon_{p;i} H_{s;i} \quad (2)$$

where i corresponds to the number of elements that constitute a certain material, $H_{s;i}$ corresponds to the thickness of each element (in m), $\varepsilon_{p;i}$ is the permanent deformation at the center of each element and δ is the cumulative permanent deformation (in m).

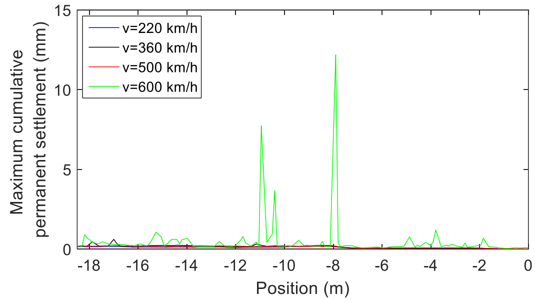
Following the developed methodology, the maximum cumulative permanent settlements occurring in the FPL and subgrade were calculated under the load alignment.

As depicted in Figure 4, the results for the subgrade and FPL reveal a clear pattern: as train speed increases, there is a corresponding increment in permanent settlements. Notably, permanent settlements are more pronounced at a train speed of 360 km/h compared to 500 km/h, although the differences between these two speeds are relatively residual. The most significant increase in permanent settlements occurs when the train speed approaches the critical speed.

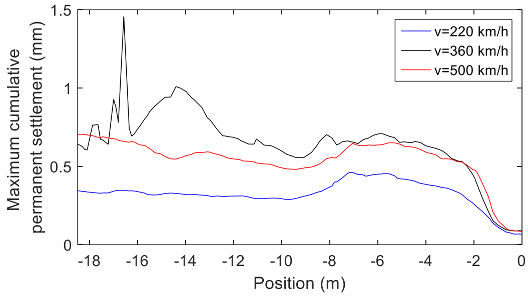
For the FPL, the results remain below the allowable deformation threshold for slab tracks in high-speed lines, typically set at 30 mm. However, in the case of the subgrade, the settlement exceeds the 30 mm limit, which can be problematic. Furthermore, it is worth noting that settlements in the subgrade are more pronounced than in the FPL. Although the magnitude of stresses is greater in the FPL, the strength properties of the track, such as cohesion and friction angle, influence the development of permanent deformation. In subgrade elements, the stress paths closely approach the yielding criterion, leading to more significant settlements.



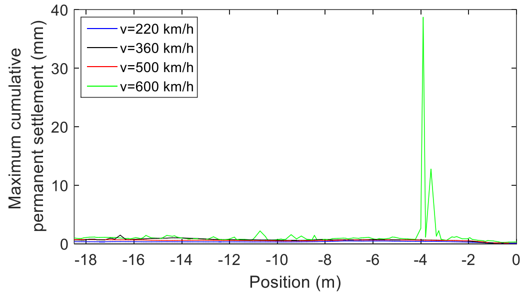
a) FPL with the train speed between 220 km/h and 500 km/h



b) FPL with the train speed between 220 km/h and 600 km/h



c) subgrade with the train speed between 220 km/h and 500 km



d) the subgrade with the train speed between 220 km/h and 600 km/h

Figure 4. Maximum cumulative permanent settlement

4 Conclusions

This study provides an in-depth analysis of the performance of a ballastless track within transition zones, with a focus on the influence of train speed, including the critical speed. A novel hybrid approach was developed to simulate track degradation, utilizing a robust and advanced 3D Finite Element Model (FEM) in ANSYS to assess the track's short-term performance. Soil settlement was simulated through the implementation of a calibrated empirical permanent deformation model.

For short-term performance, the displacements and accelerations induced in the track elements were analyzed. Both displacements and accelerations showed a direct increase with the increase in train speed. The most pronounced increase in magnitude occurred when the train speed approached the critical speed of 600 km/h.

The long-term results indicated a significant increase in settlement within the substructure when the train speed reached 600 km/h. The maximum cumulative permanent settlement exceeded allowable limits at this speed. However, for other speeds, while permanent deformation increased, the magnitude difference was not substantial.

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References

[1] Indraratna, B., M. Babar Sajjad, T. Ngo, A. Gomes Correia, and R. Kelly, *Improved performance of ballasted tracks at transition zones: A review of experimental and modelling approaches.* Transportation Geotechnics, 2019. **21**.10.1016/j.trgeo.2019.100260

[2] Ramos, A., A. Gomes Correia, R. Calçada, and D.P. Connolly, *Ballastless railway track transition zones: An embankment to tunnel analysis.* Transportation Geotechnics, 2022. **33**: p. 100728.https://doi.org/10.1016/j.trgeo.2022.100728

[3] Frohling, R.D., H. Scheffel, and W. EbersÖHn, *The Vertical Dynamic Response of a Rail Vehicle caused by Track Stiffness Variations along the Track.* Vehicle System Dynamics, 1996. **25**(sup1): p. 175-187.10.1080/00423119608969194

[4] Hunt, H.E.M., *Settlement of railway track near bridge abutments.* Proceedings of the Institution of Civil Engineers: Transport, 1997. **123**(1): p. 68-73.10.1680/itran.1997.29182

[5] Nicks, J., *The bump at the end of the railway bridge*. 2009, Texas A&M University

[6] Paixão, A., E. Fortunato, and R. Calçada, *A contribution for integrated analysis of railway track performance at transition zones and other discontinuities.* Construction and Building Materials, 2016. **111**: p. 699-709.https://doi.org/10.1016/j.conbuildmat.2016.02.126

[7] Banimahd, M., P.K. Woodward, J. Kennedy, and G.M. Medero, *Behaviour of train-track interaction in stiffness transitions.* Proceedings of the Institution of Civil Engineers: Transport, 2012. **165**(3): p. 205-214.10.1680/tran.10.00030

[8] Grossoni, I., S. Hawksbee, P. Jorge, Y. Bezin, and H. Magalhaes, *Prediction of track settlement at high-speed railway transitions between embankment and bridge in the proximity of a turnout.* Transportation Geotechnics, 2022. **37**: p. 100879.https://doi.org/10.1016/j.trgeo.2022.100879

[9] Matias, S.R. and P.A. Ferreira, *The role of railway traffic and extreme weather on slab track long-term performance.* Construction and Building Materials, 2022. **322**.10.1016/j.conbuildmat.2022.126445

[10] Gu, Q., C. Zhao, X. Bian, J.P. Morrissey, and J.Y. Ooi, *Trackbed settlement and associated ballast degradation due to repeated train moving loads.* Soil Dynamics and Earthquake Engineering, 2022. **153**: p. 107109.https://doi.org/10.1016/j.soildyn.2021.107109

[11] Ramos, A., A. Gomes Correia, R. Calçada, P. Alves Costa, A. Esen, P.K. Woodward, D.P. Connolly, and O. Laghrouche, *Influence of track foundation on the performance of ballast and concrete slab tracks under cyclic loading: Physical modelling and numerical model calibration.* Construction and Building Materials, 2021. **277**: p. 122245.https://doi.org/10.1016/j.conbuildmat.2021.122245

[12] Chen, R., J. Chen, X. Zhao, X. Bian, and Y. Chen, *Cumulative settlement of track subgrade in high-speed railway under varying water levels.* International Journal of Rail Transportation, 2014. **2**(4): p. 205–220.10.1080/23248378.2014.959083