The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 18.5
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.18.5

Numerical determination of the equivalent roughness of a realistic track for high-speed trains

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Abstract

The current paper presents a procedure to consider the effect of the geometry of the railway track on the flow under a high-speed train at a low computational cost, by using the combination of a flat wall and an equivalent roughness. For the reproduction of a realistic ballasted track, the algorithm of Voronoi´s tessellations was used to generate a statistical distribution of 3D particles with the characteristics of real ballast stones. This geometry was used in simplified simulations of an air flow over a track section to determine the value of the equivalent roughness. The simulations including only the ballast layer led to an equivalent roughness of 0.072 m, whereas when including both ballast and stones the equivalent roughness increased to 0.177 m. The adequacy of these values was satisfactorily compared with experimental results.

Next, the geometry of the underbelly of a high-speed train was included in the model, and different simulations were performed to compare the underflow generated with either a flat ground or a flat ground and the equivalent roughness. The results showed significant differences in the velocity profile, with higher values in the case of flat wall with no roughness (+13.5% in the middle of the section between ground and train), which affect to the calculation of the aerodynamic resistance. Differences were also revealed in the contours of wall shear stress on the track. The rough ground led to values up to 5 times higher, which were especially remarkable in the wake region. This behaviour would be especially significant regarding the ballast flight phenomena, and would affect to the estimation and prediction based on friction parameters. In addition, the simulations were repeated at different velocities, showing no influence on the Reynolds number.

As a conclusion, the determination and use of the equivalent roughness as a representation of the effect of the ballast and sleepers was proven as an interesting alternative in the CFD simulations of high-speed trains, showing significant differences with respect to a flat ground and avoiding the increase of the computational costs.

Keywords: ballast, CFD, underbody flow, rough ground.

1 Introduction

The evaluation of the aerodynamics of high-speed trains using computational fluid dynamics (CFD) simulations has been proved as a very interesting option that reduces the elevated cost of the experimental tests, and also offers a high flexibility in the design of the geometrical characteristics and the analysis of the boundary conditions. On the contrary, a balance between accuracy and computational expenses is required and, therefore, geometrical simplifications are usually applied.

In this regard, the rail track is often modelled as a flat wall, neglecting the contribution of the sleepers and ballast to the flow under the train. The characteristics of the flow in this region are known to be related to the aerodynamic resistance or the ballast flight phenomenon [1]. More specifically, Paz et al. developed a numerical methodology [2] and compared the flow generated by a flat track and a realistic profile of both sleepers and ballast stones [3] revealing significant differences, in agreement with experimental tests [4]. Therefore, it is proven that the geometrical characteristics of this region should be included in the CFD simulations. As a drawback, the computational cost associated to the mentioned methods is high, which might discourage the industry from using it in the iterative process of design of new trains.

As a compromise solution, the simulation of a flat ground with the equivalent roughness given by both sleepers and ballast is pointed as a very promising option. This way, aspects such as the measurement of the aerodynamic resistance would be improved. To calculate this roughness, García et al. [5] proposed analytical methods based on the turbulent approximation of a Couette flow, and Jiménez [6] reviewed the experimental evidence on turbulent flows over rough walls.

On the other hand, Rocchi et al. [7] determined it through CFD simulations by comparing the results with experimental tests. As an alternative, this study is targeted on the improvement of the determination of this equivalent roughness based on the characterisation of the ballast particles and the detailed simulations of the surrounding flow.

Thus, the objectives of this paper are the reproduction of a realistic ballasted track based on a statistical distribution of particle sizes, the determination of the equivalent roughness of both sleepers and stones, the comparison of the flow profile against a flat ground and the application of this solution to the underflow of a high-speed train.

2 Methods

The process of generation of the ballast particles was based on the design process known as Voronoi´s tessellations (Figure 1(a)). These tessellations begin with a random distribution of points and the outline of polygons in which any inner location is more close to the original point than to any other. Generalising this method to 3D, a batch of 200 polyhedral stones with different sizes and shapes were created (Figure 1(b)). The size was controlled following the distribution shown in Figure 1 (c). Then, these polyhedral stones were randomly placed reproducing the ballast layer (Figure 1(d)), and an equivalent surface that captures the ground roughness in a single wall was obtained (Figure 1(e)). The simulation of this wall leads to the estimation of the parameter of equivalent roughness of the ballast layer.

Next, sleepers with a separation distance of 600 mm were included in the geometry, and the ballast model was replicated to reproduce a section of a real track (Figure 1(f)). Again, an equivalent surface was obtained (Figure 1(g)) and simulated to obtain the value of equivalent roughness for the conjunction of both ballast and sleepers.

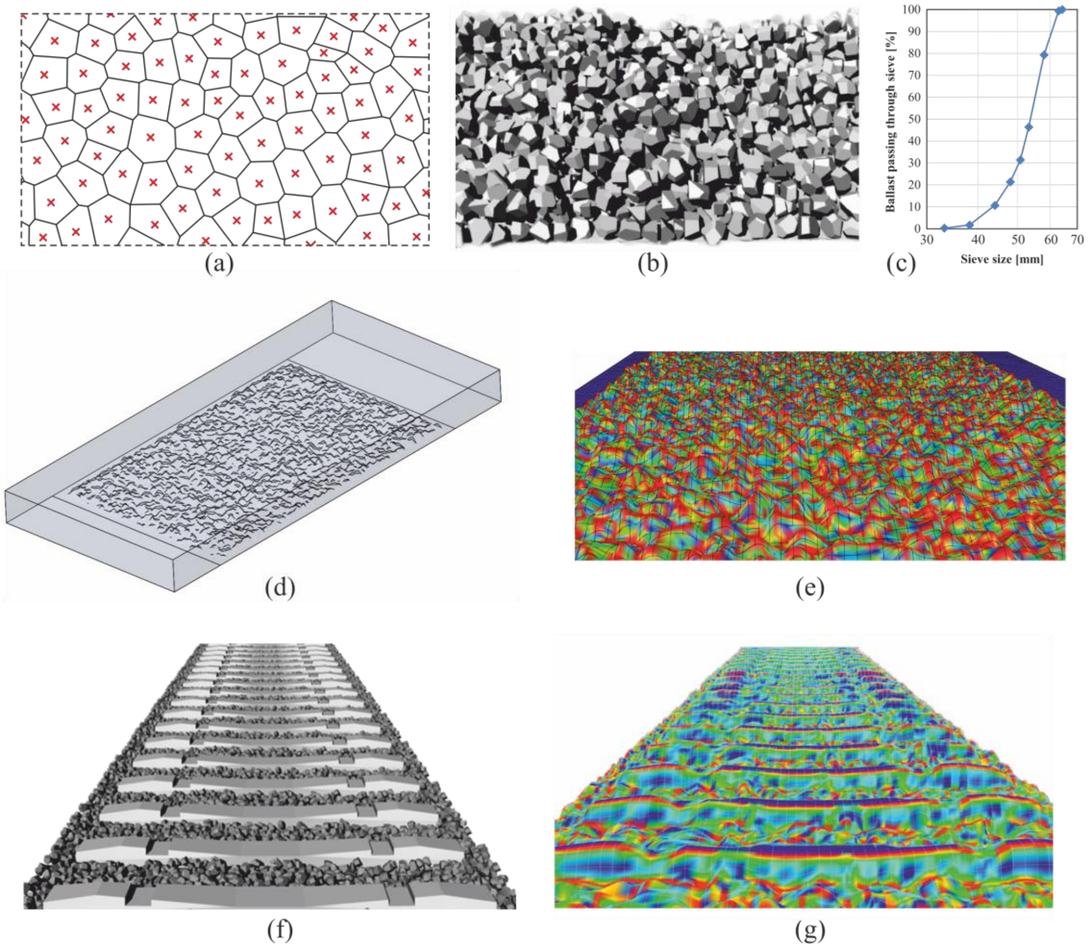

Figure 1: (a) Scheme of the 2D Voronoi Tessellations; (b) Detail of the polyhedral particles reproducing the ballast stones; (c) Graph of the size distribution of the ballast particles; (d) Reproduction of the geometry of the ballast layer; (e) Equivalent surface of the ballast layer; (f) Reproduction of real track with ballast and sleepers; (g) Equivalent surface of the real track with ballast and sleepers.

Once the track was characterised, the effect of the ground roughness on the flow under a high-speed train was evaluated. For this purpose, a geometrical model consisting of two cars with bogies was simulated. Rails were also included (Figure 2(b) and 2(c)). Details of the meshes are shown in Figure 2(c) and 2(d).

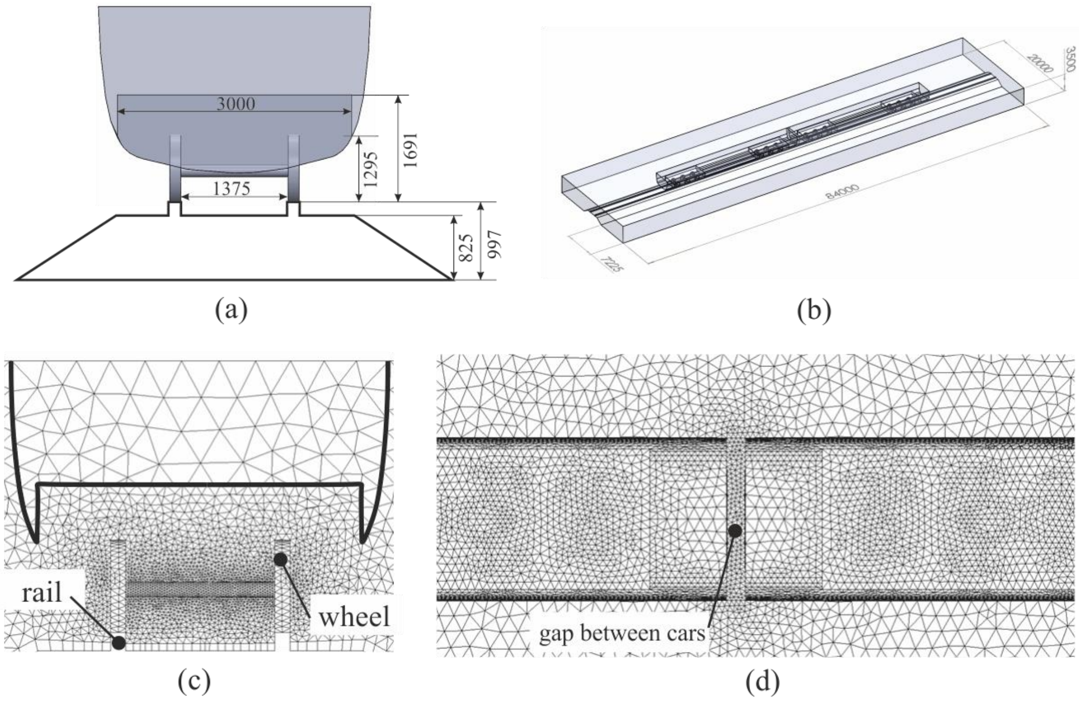

Figure 2: (a) Geometrical dimensions of the car and rails; (b) Computational domain including the geometry of two cars; (c) Detail of the mesh in the bogie region; (d) Detail of the mesh in the gap between cars.

The simulations were performed in ANSYS Fluent using the k-ε Realizable turbulent model. Incompressible air was introduced in the inlet at a velocity of 300 km/h. Both the ground and rails were defined as moving walls at the same speed to reproduce the relative movement, and the roughness followed the previously obtained values.

3 Results

The calculation of the equivalent roughness (k_s) was based on the relationship between the friction velocity (u^*) and the drag force (F), following the analytical solution of a logarithmic profile:

$$u^* = \sqrt{F/\rho L} \tag{1}$$

$$k_s = 30\left(\frac{4h^2}{0.113\pi^2 v}\right)\sqrt{\frac{F}{\rho L}}\, e^{\left[-\frac{V}{2.5}\sqrt{\frac{\rho L}{F}}\right]} \tag{2}$$

Being h the height from ground to train, L the length of the analysed section and V the reference velocity.

The simulations of both the ballast layer and the realistic track with ballast and sleepers show significant differences in the velocity field, as shown in Figure 3.

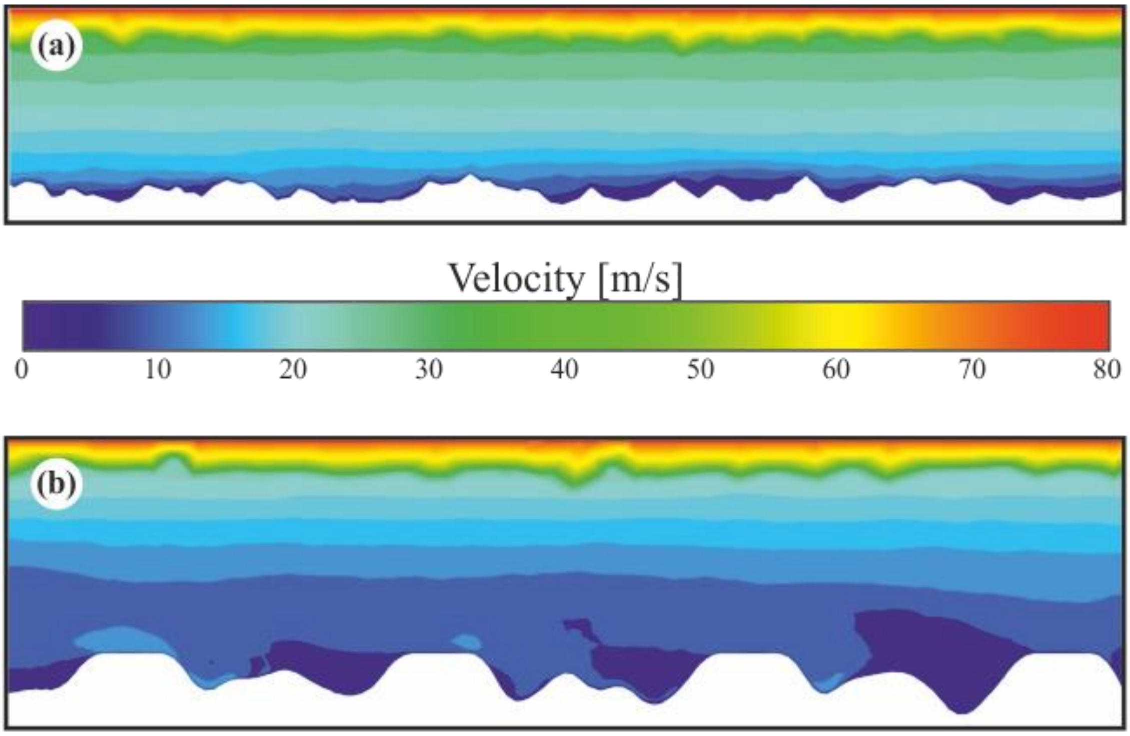

Figure 3: (a) Contours of velocity in the simulation of the ballast layer; (b) Contours of velocity in the simulation of the realistic track.

The obtained values for the equivalent roughness following Eq. (1) and Eq. (2) were 0.072 m for the ballast layer and 0.177 m for the conjunction of ballast and sleepers.

Next, the effect of using a flat ground or a ground with equivalent roughness was compared in the simulation of the flow under realistic cars. As shown in Figure 4(a), the velocity profile between the ground and the train underbelly is different. For a $z/h = 0.5$, the velocity with flat ground is 13.5% higher than in the case of rough ground. This variation would modify the measurement of the aerodynamic resistance experienced by the train. To verify these results, the obtained values of equivalent roughness were compared with the results published by Jiménez [6], as shown in Figure 4(b).

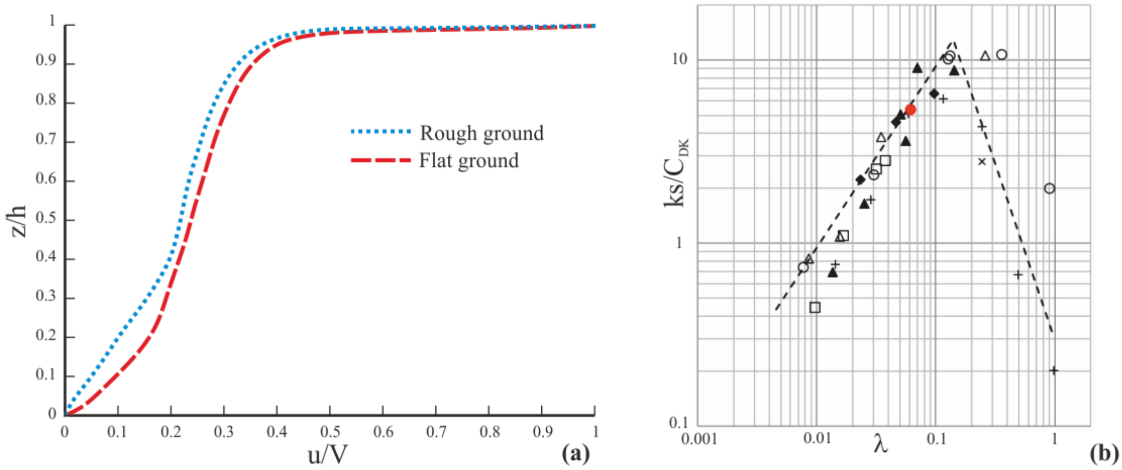

Figure 4: (a) Velocity profile between ground and train; (b) Validation of the roughness with published results.

In addition, the simulations allowed for the evaluation of the wall shear stress on the ground surface. As shown in Figure 5, the magnitude is different in both cases. It is especially remarkable than the wall shear stress in the wake region is around 4 times larger when applying the equivalent roughness on the ground. This improvement in the reproduction of the wall characteristics would be helpful in the evaluation of the ballast flight phenomena using friction parameters.

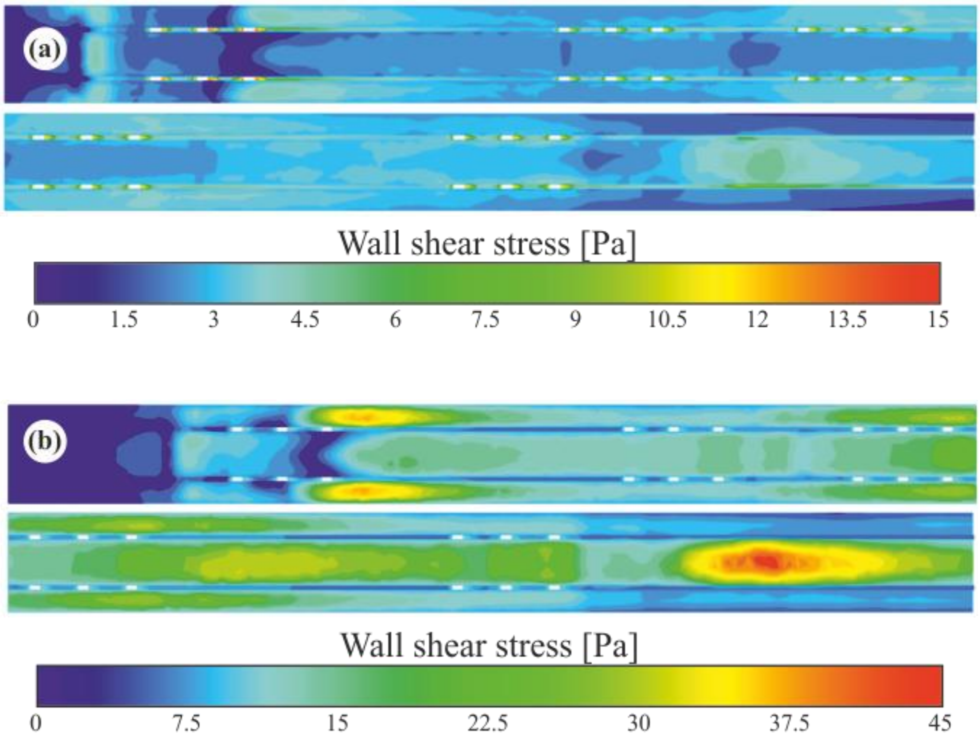

Figure 5: (a) Contours of wall shear stress on a flat ground; (b) Contours of wall shear stress on a rough ground.

4 Conclusions and Contributions

The current paper presents a procedure to consider the roughness of the railway track in the simulation of the aerodynamics of high-speed trains. Traditionally, the ground is defined as a flat surface to reduce the computational cost, but it is proven that a rough ground modifies the behaviour of the flow under the train.

The employment of the algorithm of Voronoi´s tessellations allowed for the generation of 3D particles with the characteristics of the real ballast stones. From the simulation of a layer of these stones, an equivalent roughness of 0.072 m was obtained. Including sleepers in the geometry, the equivalent roughness was 0.177 m. The adequacy of these values was satisfactorily compared with experimental results.

Next, the obtained roughness was applied as boundary condition and compared with the simulation of a flat ground. The results showed significant differences in the velocity profile, with higher values in the case of flat surface (+13.5% in the middle of the section between ground and train), which affect to the calculation of the aerodynamic resistance. These differences were also revealed in the contours of wall shear stress on the track. The rough ground led to higher values, especially remarkable in the wake. This behaviour would affect to the estimation of ballast flight phenomena based on friction parameters.

Therefore, the determination and use of the equivalent roughness as a representation of the effect of the ballast and sleepers was proven as an interesting alternative in the CFD simulations of high-speed trains, showing significant differences with respect to a flat ground and avoiding the increase of the computational costs.

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