Influence of track and vehicle wheel damages in the train running safety

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Abstract. Train running safety is an important concern because although many derailments are minor in terms of fatalities, all result in temporary rail operation disruption and they are a potentially serious hazard. Running safety is evaluated by three safety criteria based on factors related to the vehicle contact forces: the Nadal criterion, the Prud'Homme criterion and the Unloading criterion. Several research studies have focused on the assessment of the derailment risk based on monitoring measurements but as it is influenced by the existence of various conditions and environments in which the train is running, it is important to identify the factors that most influence derailment risk. In this research, the unloading criterion is used to analyze the influence of track irregularities and wheel defects such as flats, polygonization in the train running safety. The research relies on train-track dynamic responses obtained by numerical simulations. A freight train and a ballasted track are considered. A 3D wheel–rail contact model couples the train to the track by using the Hertzian theory to compute normal contact forces and tangential forces caused by rolling friction creep. The results are promising for the research purposes.

Keywords: train running safety; freight train; train–track interaction; unloading criterion.

1 Introduction

Derailments can be caused by mechanical failures of a track component, as a broken rail, mechanical failure of a component of the running gear of the vehicle, such as the axlebox, collision with another train, operational faults, such as excessive speed on a curve, high dynamic contact loads on the track-vehicle interaction, for example in extreme hunting. Although derailments are common, fatalities from train derailments are rare. According to the European Union Agency for Railways [1], in 2021, there were 78 derailments in the European Union (27 countries) with no fatalities, representing 5.6% of the total rail accident, being France and Poland the countries with the higher number of derailments (both with 14 derailments). But derailments, depending on its severity, still have a huge economic impact for society as they cause traffic disruption, track maintenance or renewal, repair or replacement of vehicle components. In the case of hazard materials transportation, derailments may also negatively affect the environment. For those reasons, it is important to control the running safety which can be evaluated by three criteria based on factors related to the vehicle contact forces. Those criteria are the Nadal criterion, the Prud'Homme criterion and the Unloading criterion, summarized in Tab. 1, where Y is the lateral dynamic contact force; Q, the vertical dynamic contact force; Q_1 and Q_2, the vertical dynamic contact forces of each side of the axle.

Table 1. Running safety criteria

Criteria	Risk of derailment	Equation	Limit [2, 3]
Nadal criterion	due to flange climbing	$\xi_N = \frac{Y}{Q}$	0.8
Prud'Homme criterion	due to the lateral contact forces	$\xi_P = \frac{\sum_{ws} Y}{10 + \frac{2}{3} \cdot Q_0}$	1.0
Unloading criterion	due to overturning	$\xi_U = 1 - \frac{Q_1 + Q_2}{2 \cdot Q_0}$	0.9

2 Numerical modelling

2.1 Vehicle

The Laagrss freight train with five wagons (Fig. 1) is considered for this study. This vehicle that can reach a top speed of 120 km/h [4] has a tare weight of 27 t and a load capacity of 52 t. A 3-D multibody dynamic model was computed in ANSYS® (2018) [5] to simulate the vehicle. The suspensions in all directions are modelled by using spring-dampers and mass-point elements are applied to represent the mass and the inertia at each wagon component's center of gravity. The mechanical and geometric properties of the vehicle can be found in [6] and a static wheel load of 106.68 kN is adopted.

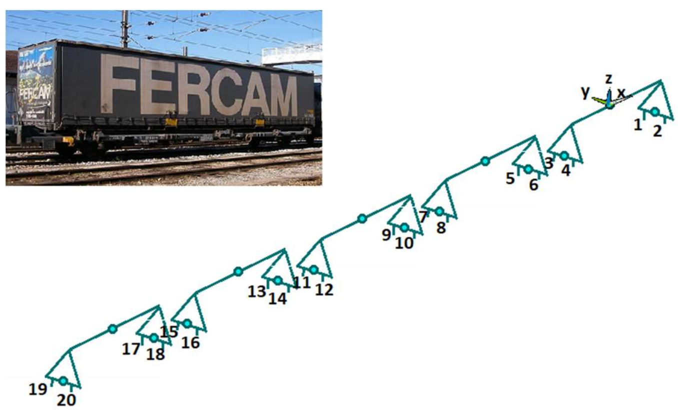

Figure 1 – Vehicle Model

2.2 Track

The track analyzed in this research is a ballasted one and the finite element model to represent it is developed with ANSYS® [5] by Montenegro et al. [7]. The model simulates the track foundation, the ballast, the sleepers, and the rails and the properties of the track elements can be found in [6].

The tracks have always some geometrical imperfections and the wheel-rail contact interaction is affected by them, thus in this study four rail unevenness profiles are generated with wavelengths corresponding to D1 interval as defined in European Standard EN 13848-2 [8]. The artificial unevenness profiles are defined by considering PSD curves. The four track profiles for right and left rails are indicated in Fig. 2.

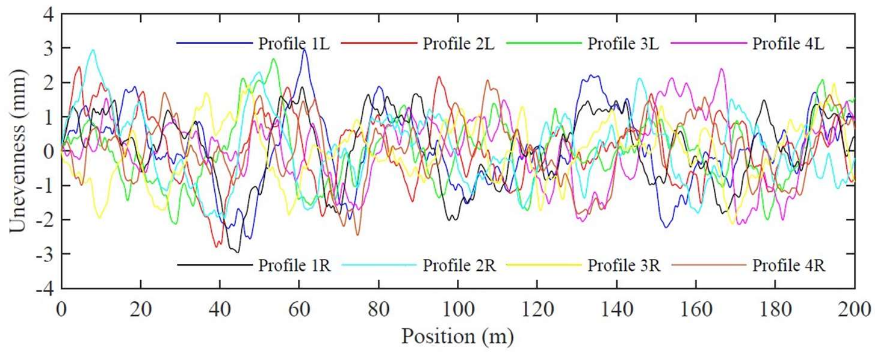

Figure 2 - Track profiles

2.3 Polygonised wheels

Polygonization is a common non-uniform wear phenomenon occurring in train wheels and influences the vehicle–track system and the ride comfort [9]. Polygonised wheels are characterized by its wavelengths (λ) that depends on the harmonic order (θ) and the wheel radius (R_w), as defined by the eq. (1):

$$\lambda = \frac{2\pi R_w}{\theta}, \quad \theta = 1,2,3 \dots, n \tag{1}$$

Wheel profiles can be generated based on the sum of n sine functions as shown in eq. (2) where A_θ is the amplitude of the sine function for each wavelength, calculated as indicated in eq. (3).

$$w(x_w) = \sum_{\theta=1}^{n} A_\theta \, sin \left(\frac{2\pi}{\lambda} x_w + \psi_\theta\right) \tag{2}$$

$$A_\theta = \sqrt{2} \cdot 10^{\frac{L_w}{20}} \cdot w_{ref} \tag{3}$$

In the present research, 30 sine functions and $w_{ref} = 1\ \mu m$ are considered. More details on modelling polygonised wheels may be found in [6,10]. To study the influence of the severity of polygonised wheels, two classes of amplitudes are analyzed: A1, corresponding to random amplitudes between 0.2 and 0.6 mm; A2, with amplitudes between 0.8 and 1.2 mm. As previously mentioned, the vehicle is composed by 5 wagons and the defective wheel is the front right wheel of the 1st wagon, the other vehicle wheels are all healthy.

2.4 Wheel flats

Wheel flats are one of the most common types of defects in wheels and induce high impact forces [11] in the track affecting significantly the running safety and causing damage to the infrastructure. The geometry of the flat is defined by considering different combination of different flat wheel depths (D) and lengths (L), as expressed by eq. (4) where R_w is the radius of the wheel.

$$D = \frac{L^2}{16R_w} \tag{4}$$

The wheel flats vertical profile is calculated as presented in eq. (5), where H represents the Heaviside function.

$$Z = -\frac{D}{2}\left(1 - cos\frac{2\pi x}{L}\right). H\big(x - (2\pi R_w - L)\big), \quad 0 \le x \le 2\pi R_w \tag{5}$$

More details on modelling wheels flats may be found in [11,12]. Three different classes of severities are considered: low (L1), medium (L2) and severe (L3). The low severity class considers flats with random lengths between 10 and 20 mm; in L2 class, the lengths vary between 25 and 50 mm and in class L3, between 55 and 100 mm and the defective wheel is located in the rear left wheel of the 3rd wagon.

2.5 Train-track interaction

A 3D wheel-rail contact model based on the Hertzian theory is used to calculate the normal contact forces. The contact forces were computed by an in-house software called VSI - Vehicle-Structure Interaction Analysis, validated and applied in several railway researches. Details on the train-track dynamic interaction can be found in [13]. The contact forces were calculated based on accelerations measured in an artificial monitoring system whose details can be found in [14].

2.6 Simulation cases

To study the influence of track irregularities and vehicle wheel damages in the train running safety, several scenarios are considered as presented in Tab. 2.

Table 2 – Considered scenarios

Variables	Healthy wheel	Damaged wheels	
		Polygonal wheel	Wheel flat
Unevenness profiles	4	1	1
Vehicle speed (km/h)	40, 60, 80, 100, 120	80, 100, 120	80, 100, 120
Severity classes	-	A1 (0.2 - 0.6 mm) A2 (0.8 - 1.2 mm)	L1 (10-20 mm) L2 (25-50 mm) L3 (55-100 mm)
Location of defect	-	front right wheel of the 1st wagon	rear left wheel of the 3rd wagon
Total of cases	20	22	63

3 Numerical results

In this section, some numerical results are presented in terms of the vertical dynamic contact load and the unloading factor for healthy wheels (Fig. 3) and for damaged wheels (Fig. 4 and 5). Figure 4 shows the results for a wagon (1st wagon) with a polygonised wheel with severity A2 and Fig. 5, for a wagon (3rd wagon) with a wheel flat with severity L3. All Figures are related to the vehicle speed of 120 km/h. In the time-histories of the vertical dynamic contact forces, the wheels numbered with an even number are on the right side of the wagon axles and the others correspond to wheels on the left side as shown in Fig. 1. The unloading factors are calculated separately for each side of the wagon as according to equation indicated on Tab. 1 and the limit of 0.9 is indicated in the corresponding figure.

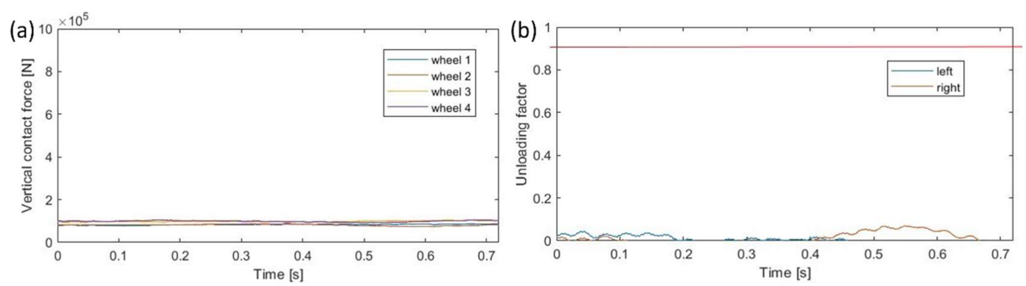

Figure 3 - Time-histories of healthy wheel: (a) vertical dynamic contact forces and (b) unloading factors

By looking to the vertical dynamic contact forces, the impact load induced by the wheel flat corresponds to 8 times the wheel static load. Also, this type of defect induces temporary loss of contact between the wheel and the rail when the dynamic load reaches zero. Polygonised wheels increase the vertical dynamic contact forces in comparison to those for healthy wheels, but that increase is not significant. The frequency of the dynamic force depends on the wavelength of the polygonised wheel.
In terms of the unloading factor, the results show that the analyzed cases do not lead to derailment as the value is inferior to 0.9. The unloading factor is neglectable for the cases of healthy wheels. It is also very small (lower that

0.3) for polygonised wheels but some differences are evident between the damaged wheel (right side) and the healthy wheel of the same wagon axle (left side). The wheel flat increases the unloading factor up to 0.55 in the side (left) of the damaged wheel and up to 0.36 in the other side of the wagon axle.

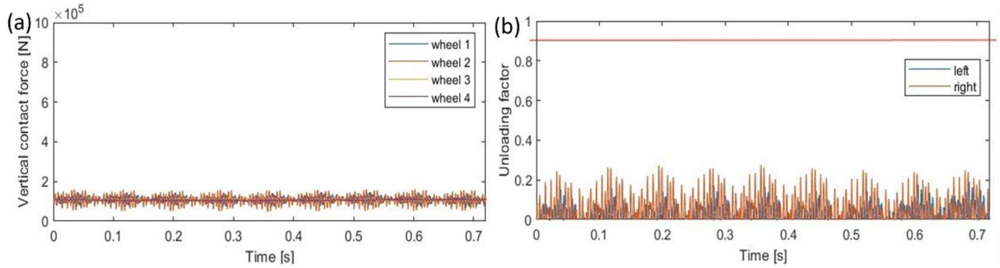

Figure 4 - Time-histories of polygonised wheel: (a) vertical dynamic contact forces and (b) unloading factors (1st wheel, right side)

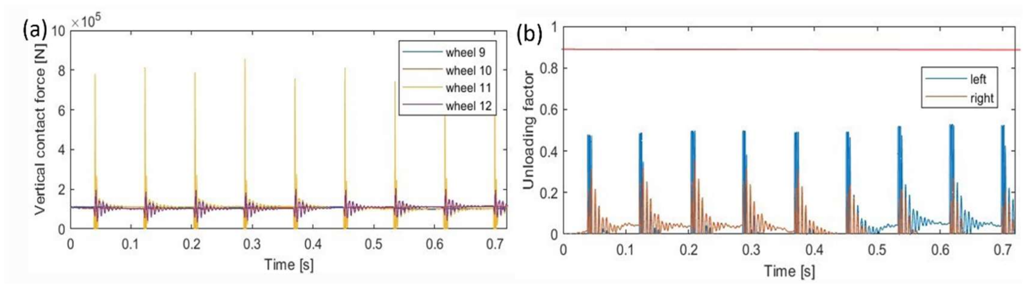

Figure 5 - Time-histories of wheel flat: (a) vertical dynamic contact forces and (b) unloading factors (11th wheel, left side)

4 Analysis results and discussion

In this section, the influence of the track profile, the vehicle speed, the type and severity of the wheel defect in the unloading factor is discussed. Also, a comparison between the unloading factor of different wagons of the same vehicle is made.

In Figure 6, the maximum unloading factor for a health wheel running at 40-120 km/h over four different track profiles is presented. All the track profiles are different as shown in Fig. 6, but correspond to the same geometrical quality class (a good one). From the results, it can be seen that the track profile does not significantly affect the unloading factor for healthy wheels.

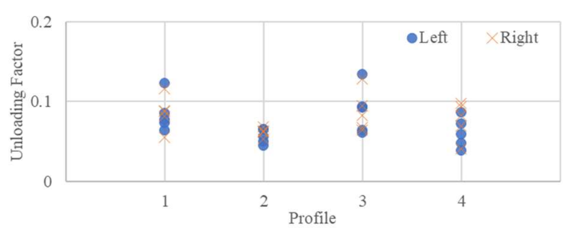

Figure 6 - Influence of the track profile in the unloading factor of a healthy wheel.

Figure 7 presents the maximum unloading factor for different speeds and for a healthy wheel, a polygonised wheel and a wheel flat. In order to have a fairly representative sample for analysis, for the damaged wheels a great number of random wheel profiles were considered for the speeds of 80 and 100 km/h. This has been done for the speeds of 80 and 100 km/h, because these are the most common vehicle speed of a freight train running over a monitoring system. It can be seen that the vehicle speed does not seem to influence the unloading factor contrary to the defect severity. The comparison of the maximum unloading factor for different severity (vehicle speed vary between 80 and 120 km/h) is shown in Figure 8. In the axle with a polygonised wheel, the unloading factor can reach 0.4 in the side of the defect, an increase of 60 % in comparison to the unloading factor for the other side of the same axle.

For axle with flats, the unloading factor can be up to 0.55, which is 150 % higher than the unloading factor for the wheel of the other side of the same axle.

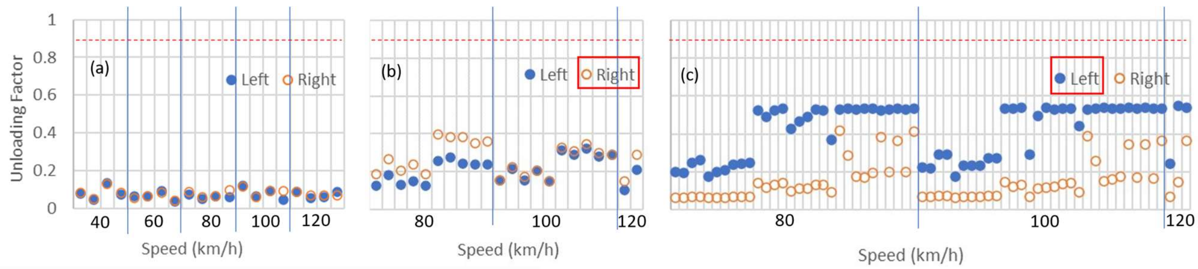

Figure 7 - Influence of the vehicle speed in the unloading factor (a) healthy wheel; (b) polygonised wheel (right side); (c) wheel flat (left side).

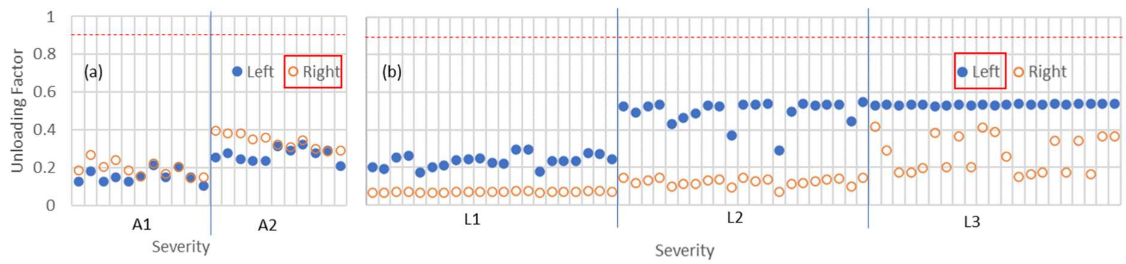

Figure 8 - Influence of the severity of the defect in the unloading factor (a) healthy wheel; (b) polygonised wheel (right side); (c) wheel flat (left side).

In order to analyze the variation of the unloading factor in the longitudinal and transversal direction of the freight vehicle, the factor was computed for the left and right side of the two consecutive wagons most near to the defected axle (Fig. 9 and 10). In these Figures, the negative values of the unloading factor are not relevant for the running safety as they correspond to positive dynamic loads (as expression of unloading criterion explains), that influences essentially the track and the vehicle dynamics. The results show that the variation of the (positive) unloading factor is higher in the faulty wagon being reduced in the consecutive wagons. For polygonised wheel defect the unloading factor is already neglectable in the second wagon most near to the defected one, but for the cases of wheel flats the unloading factor in the nearest wagon is still influenced by the defect.

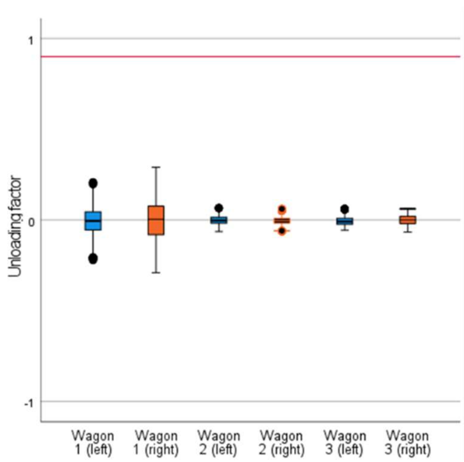

Figure 9 - Boxplots of the unloading factor for the faulty wagon and on the next 2 consecutive wagons-polygonised wheel (1st wagon, right side)

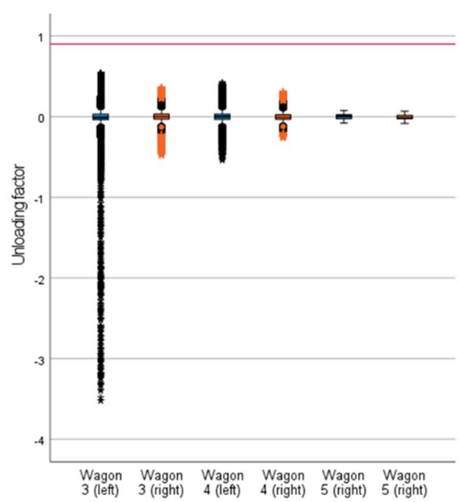

Figure 10 - Boxplots of the unloading factor for the faulty wagon and on the next 2 consecutive wagons-wheel flat (3rd wagon, left side)

5 Conclusions

The findings of this study provide clear insights into the influence of the track irregularities and the wheel defects such as flats, polygonization in the unloading factor, one of the three criteria for assessing derailment risk. The results show that the unloading factor is neglectable for the cases of healthy wheels being also very small for polygonised wheels. The wheel flats induce higher unloading factors, but for the cases in analysis still far from the limit for derailment. The analysis of the results also confirms that the track profile (good geometrical quality) and the vehicle speed does not significantly affect the unloading factors contrary to the defect severity.

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Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property and authorship of the authors.

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