CETRA[2018]

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

Organizer
University of Zagreb
Faculty of Civil Engineering
Department of Transportation

CETRA[2018]
5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

TITLE
Road and Rail Infrastructure V, Proceedings of the Conference CETRA 2018

EDITED BY
Stjepan Lakušić

ISSN
1848-9850

ISBN
978-953-8168-25-3

DOI
10.5592/CO/CETRA.2018

PUBLISHED BY
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE
minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY
“Tiskara Zelina”, May 2018

COPIES
500

Zagreb, May 2018.

Proceedings of the
5th International Conference on Road and Rail Infrastructures – CETRA 2018
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

EDITOR
Stjepan Lakušić
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Zagreb, Croatia

ORGANISATION

CHAIRMEN

Prof. **Stjepan Lakušić**, University of Zagreb, Faculty of Civil Engineering
Prof. emer. **Željko Korlaet**, University of Zagreb, Faculty of Civil Engineering

ORGANIZING COMMITTEE

Prof. Stjepan Lakušić
Prof. emer. Željko Korlaet
Prof. Vesna Dragčević
Prof. Tatjana Rukavina
Assist. Prof. Ivica Stančerić
Assist. Prof. Maja Ahac
Assist. Prof. Saša Ahac
Assist. Prof. Ivo Haladin
Assist. Prof. Josipa Domitrović
Tamara Džambas
Viktorija Grgić
Šime Bezina
Katarina Vranešić
Željko Stepan
Prof. Rudolf Eger
Prof. Kenneth Gavin
Prof. Janusz Madejski
Prof. Nencho Nenov
Prof. Andrei Petriaev
Prof. Otto Plašek
Assist. Prof. Andreas Schoebel
Prof. Adam Szeląg
Brendan Halleman

INTERNATIONAL ACADEMIC SCIENTIFIC COMMITTEE

Stjepan Lakušić, University of Zagreb, president
Borna Abramović, University of Zagreb
Maja Ahac, University of Zagreb
Saša Ahac, University of Zagreb
Darko Babić, University of Zagreb
Danijela Barić, University of Zagreb
Davor Brčić, University of Zagreb
Domagoj Damjanović, University of Zagreb
Sanja Dimter, J. J. Strossmayer University of Osijek
Aleksandra Deluka Tibljaš, University of Rijeka
Josipa Domitrović, University of Zagreb
Vesna Dragčević, University of Zagreb
Rudolf Eger, RheinMain Univ. of App. Sciences, Wiesbaden
Adelino Ferreira, University of Coimbra
Makoto Fujiu, Kanazawa University
Laszlo Gaspar, Széchenyi István University in Győr
Kenneth Gavin, Delft University of Technology
Nenad Gucunski, Rutgers University
Ivo Haladin, University of Zagreb
Staša Jovanović, University of Novi Sad
Lajos Kisgyörgy, Budapest Univ. of Tech. and Economics
Anastasia Konon, St. Petersburg State Transport Univ.
Željko Korlaet, University of Zagreb
Meho Saša Kovačević, University of Zagreb
Zoran Krakutovski, Ss. Cyril and Methodius Univ. in Skopje
Dirk Lauwers, Ghent University
Janusz Madejski, Silesian University of Technology
Goran Mladenović, University of Belgrade
Tomislav Josip Mlinarić, University of Zagreb
Nencho Nenov, University of Transport in Sofia
Mladen Nikšić, University of Zagreb
Andrei Petriaev, St. Petersburg State Transport University
Otto Plašek, Brno University of Technology
Mauricio Pradena, University of Concepcion
Carmen Racanel, Tech. Univ. of Civil Eng. Bucharest
Tatjana Rukavina, University of Zagreb
Andreas Schoebel, Vienna University of Technology
Ivica Stančerić, University of Zagreb
Adam Szeląg, Warsaw University of Technology
Marjan Tušar, National Institute of Chemistry, Ljubljana
Audrius Vaitkus, Vilnius Gediminas Technical University
Andrei Zaitsev, Russian University of transport, Moscow

CETRA2018 17–19 May 2018, Zadar, Croatia
5th International Conference on Road and Rail Infrastructure

ANALYSIS OF DYNAMIC IMPACT FORCES ON RAILWAY TRACKS DUE TO WHEEL FLATS

Cengiz Kolukirik[1], **Niyazi Özgür Bezgin**[2]
[1] *Istanbul Gelisim University, Turkey*
[2] *Istanbul University, Turkey*

Abstract

Vertical dynamic impact forces on railway tracks develop as a result of train speed and vehicle-track interactions. Variations in track profile and track stiffness as well as variations in wheel circularity influence the dynamic impact forces that are mutually transferred between the track and the wheel of a speeding train. Today, there are various methods for predicting vertical dynamic impact forces. Most of these methods are based on empirical studies, and few others are analytical in nature. These equations can be evaluated under three main categories: equations that concentrate on vehicle properties, equations that concentrate on track properties and equations that consider both the train and the track properties. This paper presents an analytical equation that is developed based on a new analytical method proposed by Dr. Bezgin from Istanbul University, which explicitly correlates the instantaneous vertical impact forces generated by the wheels of a moving train to train speed, track stiffness and track or wheel irregularities. This paper concentrates on the effects of wheel flats on vertical wheel forces and proposes an equation that estimates the vertical impact forces due to train speed, wheel diameter, track stiffness and the depth and the length of the wheel flat. The proposed equation relies on the principle of conservation of energy, rules of kinematics, geometry, Hertzian contact theory and a new concept of impact reduction factor. The occurrence of the dynamic impact forces at different train speeds and wheel flat dimensions will be investigated based on different wheel diameters and track stiffness values. The results with respect to the effects of wheel flat dimensions on the vertical impact forces will be compared with the limitations for the wheel flats provided in the UIC Code 510.

Keywords: Dynamic impact forces, track irregularities, track stiffness, wheel flats, impact reduction factor

1 Introduction

Occurrence of a wheel flat is the most common type of wheel failure encountered in the railway industry due to wheel slip on the rail during braking when the braking force is greater than the existing wheel-rail friction or when the braking system is poorly adjusted [1]. During acceleration and deceleration phases of a train, the part of the wheel that contacts the rail undergoes horizontal deformations additionally to vertical deformations. The repetition of such movements may also result in a flat surface along the wheel that locally changes the circularity of the wheel.

This surface irregularity causes impact forces on the track when the wheel rolls over the track. Depending on the number of wheel flats, speed of the train and wheel diameter, this impact force causes high frequency vibrations in the line and vehicle components. It has been seen that the overburden of the impact force can even break the rail [2].

DOI: https://doi.org/10.5592/CO/CETRA.2018.905

This paper presents the development of an analytical equation that estimates the impact forces due to wheel flats. The equation basis on a proposed method and a proposed concept by Bezgin [3-5]. From this new dynamic impact estimation method, the developed equation by Kolukırık and Bezgin estimates the dynamic impact forces based on different track stiffness values, wheel diameters and wheel flat dimensions.

2 Vehicle – Track Interaction in Railways

The vertical elastic track stiffness is the force that must be applied at a point on the track to generate a unit elastic deformation in the vertical direction. Track stiffness is a function of the deformational properties of the components that form a track. If the vertical force is the wheel force “P” that causes the vertical rail deformation “y”, the track stiffness per rails “k” relates to the force and the deformation as in Eq. (1):

$$k = \frac{P}{y} \tag{1}$$

The track stiffness per rail of the track superstructure is revealed by the combined effect of the unit resistance values of the various layers forming the track.

2.1 Dynamic Impact Force Estimation

The vertical force applied by the wheel of a moving train is instantaneous and vibrates the track. Therefore, this force is referred to as a dynamic impact force [3]. The dynamic impact force that develops due to track or train irregularities is greater than the static force of the wheel, which relates to the static weight of the tributary mass of the wheel. Dynamic impact forces “P_d”; can be conceptually expressed in terms of the static wheel force “P_s” and the dynamic impact force factor “φ” as presented in Eq. (2):

$$P_d = \phi P_s \tag{2}$$

2.2 A New Method of Dynamic Impact Forces Estimation on Railway Tracks

Fig. 1 is a sketch of a train wheel rolling over a descending track profile. In this figure, “a” is the amount of displacement under the static train force on the track and “c” is the amount of displacement under the dynamic impact force on the track. The rough length of track along which profile deviation occurs is “L” and the new deviation of profile is “h”.

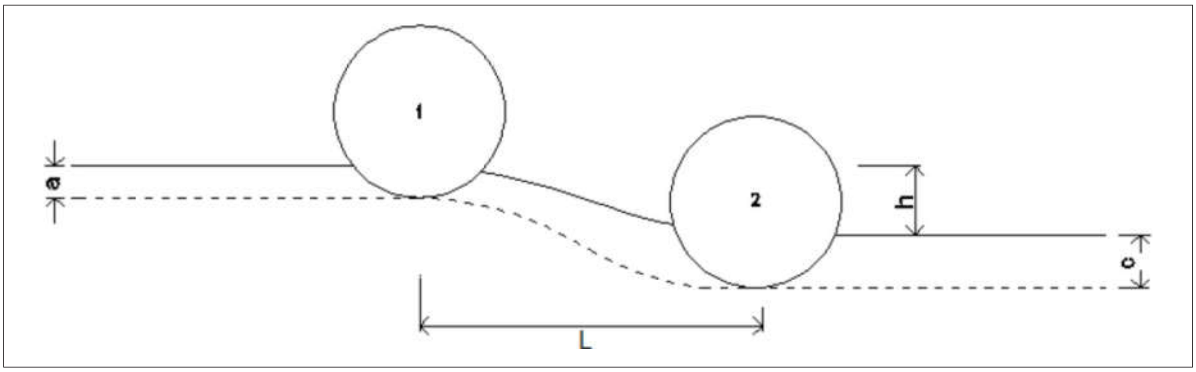

Figure 1 A track with vertical irregularities due to superstructure problems [4]

Eq. (3) introduces the fundamental “f” parameter, which is the basis of the method to be presented and is developed by and referred to as the “impact reduction factor” by Bezgin [1-3].

The impact reduction factor, hypothetically relates the time to freely fall from a vertical height of "h" to the time required for the wheel to pass over the rough track length of "L" and relates the impact reduction factor to t_{pass} and t_{fall}.

$$f = 1 - \frac{t_{fall}}{t_{pass}} \tag{3}$$

Eq. (4) and Eq. (5) define the t_{pass} and t_{fall} values based on rules of kinematics where "v" is the train speed and "g" is the gravitational constant of earth.

$$t_{fall} = \sqrt{\frac{2h}{g}} \tag{4}$$

$$t_{pass} = \sqrt{\frac{L}{V}} \tag{5}$$

Eq. (6) relates the highest impact displacement of the rail to its static displacement.

$$c = a\left(1 + \sqrt{2h/_{a}\,(1-f)}\right) \tag{6}$$

Eq. (7) represents the dynamic impact force factor ($K_{B,d}$), which provides an estimate for the dynamic impact forces that develop over a descending track profile irregularity [3,4].

$$K_{B,d} = 1 + \sqrt{2h/_{a}\,(1-f)} \tag{7}$$

The track irregularity that generates the vertical impact force in the presented case is the variation of the track profile "h". Verification of Eq. 7 with other equations are presented elsewhere and therefore will not be repeated here [3-5]. The following section introduces the development of impact forces due to wheel flats where the particular irregularity that generates the impact is the depth and length of the wheel flat.
Proposal of an Equation for to Estimate the Dynamic Impact Forces Due to Wheel Flats Fig. 2 presents the sketch of wheel flat on a wheel with a certain radius "r". If we draw lines from the start point "A" and the end point "B" of the flattened length from the centre of the wheel, we get an isosceles triangle with an apex angle of θ.

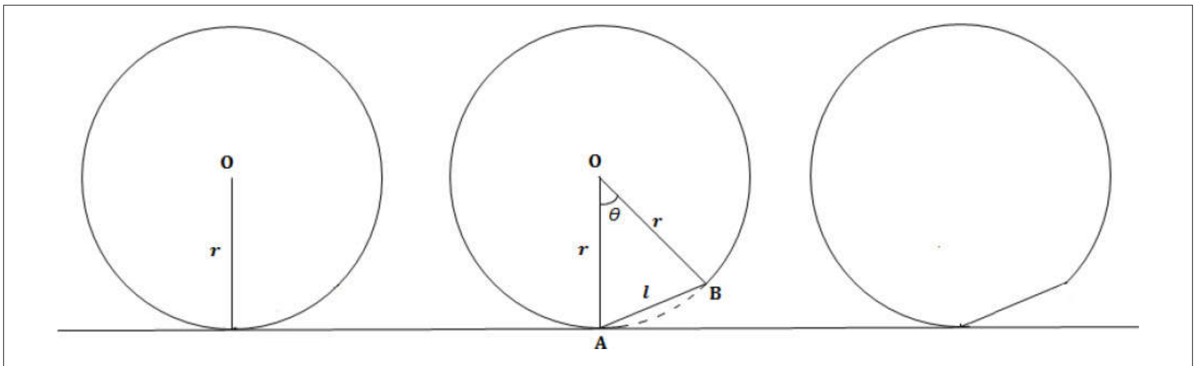

Figure 2 View of wheel flat (not to scale) [6].

By equally dividing the apex angle of this isosceles triangle, we obtain two right-angled triangles as shown in Fig. 3. If we draw a vertical line from point B to the horizontal line below, we obtain a third right-angled triangle. By using these triangles, we can relate the length of the wheel flat to the radius of the wheel.

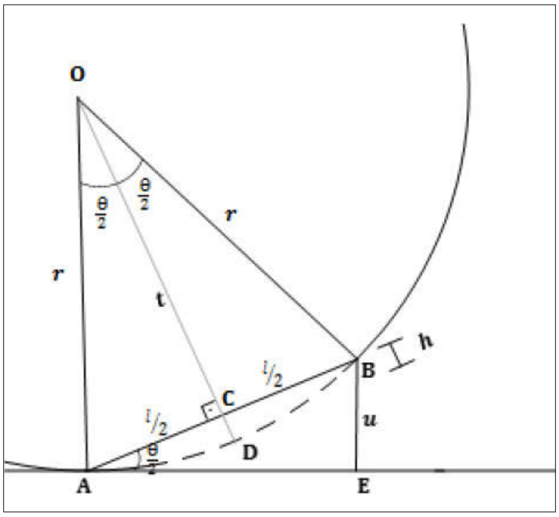

Figure 3 Geometric presentation of the vicinity of the wheel flat. (not to scale) [6]

The "u" value is the vertical distance between the comprising triangle of wheel flat and rail as indicated in Eq. (8).

$$u = l \cdot \sin\frac{\theta}{2} = 2r \cdot \sin\frac{\theta}{2}\sin\frac{\theta}{2} = 2r \cdot \sin^2\frac{\theta}{2} \tag{8}$$

Eq. (9) defines the time it takes to spin around the point A and relates it to the angular speed of the wheel. This value represents the effect of the time to pass value presented before for the t [3-5].

$$t_{spin} = \frac{\theta}{2} \Big/ w = \theta \cdot r / 2 \cdot V \tag{9}$$

Eq. (10) relates the time for point B to vertically impact the horizontal line.

$$t_{fall} = \sqrt{\frac{2u}{g}} = \sqrt{\frac{4r}{g}\sin\frac{\theta}{2}\sin\frac{\theta}{2}} = 2 \cdot \sin\frac{\theta}{2}\sqrt{\frac{r}{g}} \tag{10}$$

Eq. (11) represents the impact reduction factor "f".

$$f = 1 - \frac{t_{fall}}{t_{spin}} = 1 - \frac{2 \cdot \sin\frac{\theta}{2}\sqrt{\frac{r}{g}}}{\theta \cdot \frac{r}{2} \cdot V} = 1 - \frac{4 \cdot V \cdot \sin\frac{\theta}{2}\sqrt{\frac{r}{g}}}{\theta \cdot r} \tag{11}$$

Eq. (12) presents the factor to estimate the dynamic impact force proposed by Kolukırık and Bezgin [6]. This equation is named as K_{B3} since this is the fifth equation after four equations that are named as $K_{B,d}$, $K_{b,a}$, K_{B1} and K_{B2} developed in earlier studies by Bezgin [3-5]. $K_{B,d}$ and

$K_{b,a}$ are impact factor equations for descending and ascending track profiles, K_{B1} and K_{B2} are impact factor equations for decreasing and increasing track stiffness conditions.

$$K_{B3} = 1 + 2 \cdot \sqrt{\frac{2h}{a}\left(\frac{V \cdot \sin\frac{\theta}{2}\sqrt{\frac{r}{g}}}{\theta \cdot r}\right)} \tag{12}$$

The "u" value represented earlier was only geometrically obtained by assuming that the contact at point A was between infinitely rigid rail and wheel. However this is not the case and according to the Hertz contact theory the point A flattens a certain amount thereby reducing the value of "u", as shown in Fig. 4.

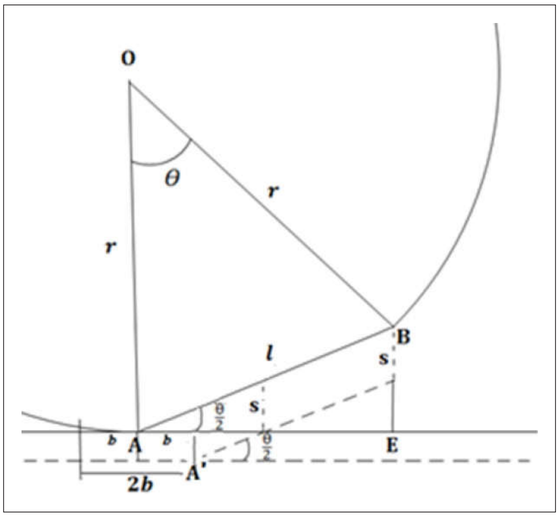

Figure 4 Figure 4. Geometric presentation of the vicinity of the wheel flat including the local deformations due to Hertzian Contact (not to scale) [6]

Details for this development are present elsewhere and cannot be presented here due to space limitations [6]. However, the result of the geometric analysis showed that the revised u value "u'" due to deformation at point A is approximately 40% of the former u value. Eq. (13) is a revised presentation of Eq. (12) with a consideration of the Hertzian deformation at point A where the wheel contacts the rail [6].

$$K_{B3} = 1 + 2 \cdot \sqrt{\frac{2h}{a}\left(\frac{V \cdot \sin\frac{\theta}{2}\sqrt{\frac{0,4 * r}{g}}}{\theta \cdot r}\right)} \tag{13}$$

Limitations are imposed on the allowable wheel flat length according to the UIC 510 and Railway Group Standard GM/RT2466. Table 1 shows the dynamic impact factor estimates for a wheel flat length limit of l=30 mm for three different wheel diameters of D=780 mm, 860 mm and 920 mm for three different track stiffness per rail values of k = 85 kN/mm, 42.5 kN/mm and 28.3 kN/mm. Under an axle force of 170 kN, the static deflection of the wheels are a = 1 mm, 2 mm and 3 mm respectively.

Table 1 Dynamic impact force factors for different wheel diameters [6]

Speed km/h	Speed m/s	l [mm]	Θ/2 [rad]	w=v/r [rad/s]	h [mm]	u [m]	b [mm]	s+ΔL [m]	u' [s]	t_{spin} [s]	t_{fall} [s]	f	K_{B3} a=1 mm	K_{B3} a=2 mm	K_{B3} a=3 mm
D = 780 mm															
0	0.0			0.0						0		0	1	1	1
50	13.9			35.6						0.0011		-8.1	3.94	3.08	2.70
100	27.8	30	0.038	71.2	0.29	0.0012	8.55	0.00068	0.0005	0.0005	0.0098	-17.2	5.15	3.94	3.40
150	41.7			106.8						0.0004		-26.3	6.09	4.60	3.94
200	55.6			142.5						0.0003		-35.4	6.87	5.15	4.39
D = 860 mm															
0	0.0			0.0						0		0	1.00	1.00	1.00
50	13.9			32.3						0.0011		-7.3	3.57	2.82	2.48
100	27.8	30	0.035	64.6	0.26	0.0010	10.37	0.00065	0.0004	0.0005	0.0090	-15.6	4.63	3.57	3.10
150	41.7			96.9						0.0004		-24.0	5.45	4.15	3.57
200	55.6			129.2						0.0003		-32.3	6.14	4.63	3.97
D = 920 mm															
0	0.0			0.0						0		0	1.00	1.00	1.00
50	13.9			30.2						0.0011		-6.8	3.33	2.65	2.35
100	27.8	30	0.033	60.4	0.24	0.0010	10.73	0.00063	0.0003	0.0005	0.0084	-14.6	4.30	3.33	2.90
150	41.7			90.6						0.0004		-22.4	5.04	3.85	3.33
200	55.6			120.8						0.0003		-30.2	5.66	4.30	3.69

The proposed method captures the increase in dynamic impact forces with decreasing wheel diameters and increasing track stiffness values. For a given wheel flat length of 30 mm, as the wheel curvature increases with decreasing diameter, the depth of the flat and hence the impact height u' increases. Note that the effective impact height u' due to Hertzian contact evaluation is roughly 40 % of the impact height for the perfectly rigid contact condition. Fig. 5 clearly shows that for a wheel flat length of 30 mm, increased track stiffness increases the impact forces with speed.

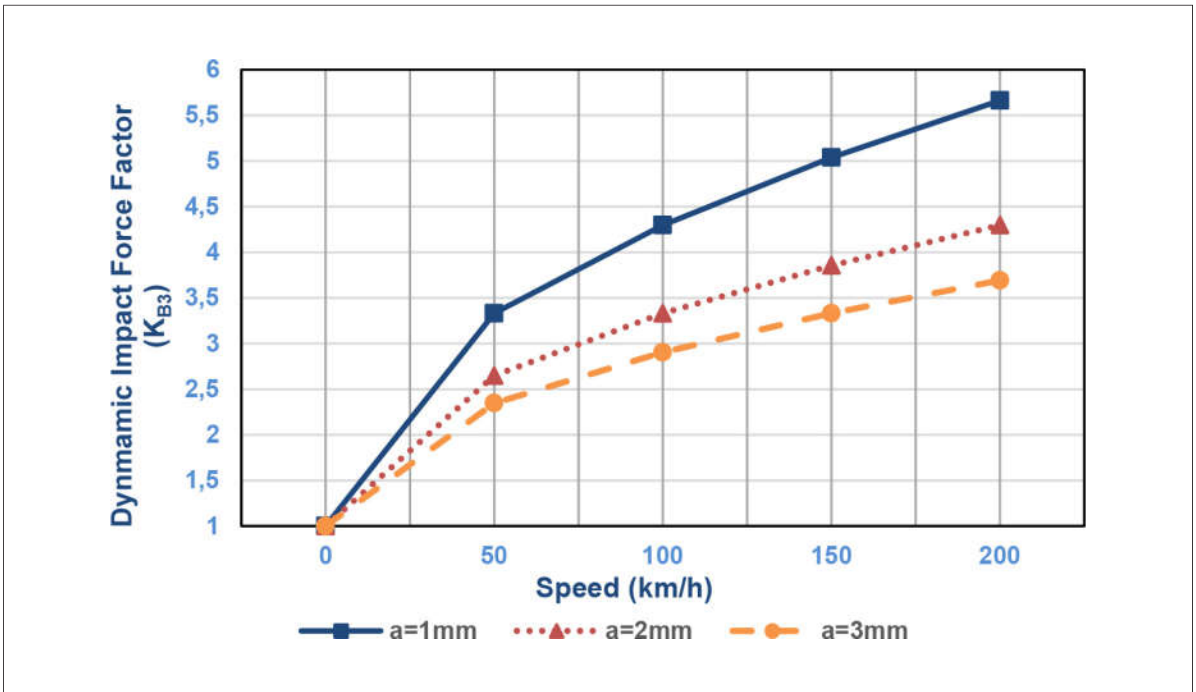

Figure 5 Dynamic impact force factors for 920 mm diameter wheel [6]

3 Discussion and future work

This paper introduced an analytical equation that estimates the dynamic impact force values of a moving train wheel imposed on a railway track due to wheel flats. The conceptual basis of the proposed method relies on the principle of conservation of energy, kinematics and a new concept of impact reduction factor. These concepts are further advanced in this paper with geometry to propose an equation that clearly includes the effects of the length of the wheel flat, along with the diameter of the wheel, the speed of the train and the track stiffness per rail. The proposed method is applied to analyse the impact of wheel flats for three different wheel diameters. Although "t_{spin}" is the same in all diameters, the "t_{fall}" decreases as the diameter of the wheel increases for a wheel flat. Therefore, for a given speed and wheel flat, "f" is inversely proportional to the wheel diameter. As the static displacement increases when the track stiffness decreases, the dynamic impact force also decreases for a given speed and wheel flat length, thereby showing the effect of the stiffness of track on the impact.
The proposed equation provides its beneficiary with a practical analytical tool to estimate the effects of wheel flats on train wheels. To the knowledge of its authors, it is the first such equation to estimate the dynamic impact forces due to wheel flats. The proposed method and its results are currently validated with a limited number of direct measurements from railway tracks and the estimated results are so far in agreement with the measured forces from actual train wheels with flats. Nevertheless, further comparisons are underway. The proposed equation is also advanced with the inclusion of wheel and bogie stiffness and damping.

References

[1] Sun, Y.Q., Dhanasekar, M.: A dynamic model for the vertical interaction of the rail track and wagon system, International Journal of Solids and Structures 39, pp. 1337–1359, 2002.

[2] Ishida, M., Ban, T.: Modelling of the wheel flats for track Dynamics, XXX. Convegno Nazionale AIAS-Alghero (SS), 12-15 September 2001.

[3] Bezgin, N.O.: Development of a new and an explicit analytical equation that estimates the vertical impact loads of a moving train. Procedia Engineering, Volume 189, 2017, Pages 2-10.

[4] Bezgin, N.O.: Application of a new concept and a new method to estimate the vertical impact forces on railway tracks due to track profile irregularities. 97th Transportation Research Board Meeting, Washington DC, Paper: 18-00037. 2018.

[5] Bezgin N.O.: Application of a new concept and a method to estimate the vertical impact forces on railway tracks due to track stiffness variations. 97th Transportation Research Board Meeting, Washington DC, Paper: 18-00407. 2018.

[6] Kolukirik, C.: A Mathematical Evaluation Of Vertical Vehicle Loads Based On Lateral Motion Of Vehicle, M.Sc. Thesis , İstanbul University Institute of Graduate Studies in Science and Engineering, İstanbul, Turkey, 2017.

[7] UIC 510-2 OR: Trailing stock: wheel and wheelset, condition concerning the use of wheel of various diameters, UIC, Paris, France, 2004.

[8] Railway Group Standard GM/RT2466: Railway Wheelsets, London, England, 2010.