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17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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PROPOSAL OF A NEW ANALYTICAL METHOD TO ESTIMATE THE VERTICAL IMPACT FORCES ON RAILWAY TRACKS DUE TO CHANGES IN TRACK PROFILE AND TRACK STIFFNESS

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Abstract

Profile and stiffness variations along a railway track generate dynamic impact forces of a moving train on the railway track. A full mechanical evaluation of the interaction between the train and the track is a complex issue due to the presence of many mutually interactive mechanical and geometrical parameters and therefore requires the use of iterative analytical procedures conducted by advanced software. Observations and data collection along a rough length of track where the track profile and/or the track stiffness varies, supplement the efforts to understand and evaluate the reasons for and the outcomes of these variations. Nevertheless, the large amount of data and the longevity of the time required for such analysis create difficulties in the assessment of the effects of a rough length of track on the railway services. Engineers, frequently lack the time, the tool or the budget to assess in detail the impact of a roughened length of track on the railway service. Today, the effects of variations in track stiffness and track profile on the impact forces that may occur as the track traverses bridges and tunnels or passes over culverts, as well as the effects of variations due to ballast fouling, frost, rail corrosion or breakage and track drainage problems are still issues that require practical methods for their assessment. To this end, the author developed a method that relies on the principle of conservation of energy, rules of kinematics and a new concept of impact reduction factor. The method yielded four equations that can estimate the dynamic impact forces due to ascending and descending track profiles and increasing or decreasing track stiffness values. This paper introduces the equation for the impact that develops due to an ascending track profile and provides some of the practical findings of the proposed method.

Keywords: Railway track, track profile variations, track stiffness variations, stiffness transition, dynamic impact forces, impact reduction factor, Bezgin Impact Factors

1 Introduction

Railway track profile and/or stiffness can vary along certain lengths of track. This variability can be limited by tolerances based on railway track construction specifications to limit their effects. However, this variability can also become operationally significant due to poor track construction practices or variations in track profile and/or stiffness that develop in time. Such variations, which will be named as “track roughness”, may lead to reduced passenger comfort, increased track maintenance requirements and compromised operational safety of the train.
Track roughness can increase the vertical train wheel forces beyond their static values. In the early days of railway track engineering when the available theoretical background and the tools to evaluate the multitude of interacting parameters were limited, researchers conducted empirical studies supported by site-work to evaluate their analytical insights into the railway track behaviour under the moving train. Many researchers have empirically and statistically

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investigated the effects of track roughness on the increased vertical wheel forces on the railway track. Today, we have an account for most of the available empirical approaches that estimate the vertical impact forces [1]. In time, analytical estimation of the increased forces became possible as the theoretical background of railway engineering expanded and the means to collect and evaluate track data increased [2, 3, 4]. The computerized techniques such as finite element analysis and discrete element analysis to evaluate the effects of interacting parameters also advanced [5]. The wealth of analytical work conducted by advanced computerized techniques keeps accumulating, which are thoroughly reviewed in select literature [6]. Track designers frequently resort to advanced analytical methods to estimate the effects of particular track conditions on the developing forces or to design a track for certain operational conditions. However, these methods are not simple and they can be hardly conducted manually and their results can be hardly verified manually. One would need to gather track parameters from a particular site and use commercial or custom-made software to develop a model, which is an estimate of the actual track and conduct an analysis to find a solution for an array of simultaneously solved equations. In the absence of such software, one must resort to empirical equations to acquire an estimate for the developing forces. However, the applicability's of these equations are limited and the particular conditions which generated them are seldom known in detail, thereby raising a question for their applicability for a certain track and rolling stock condition. Today, railway engineers and researchers lack a simple analytical method to provide them with an estimate of the possible dynamic impact forces due to a speeding train over a rough length of a railway track.
To this end, the author developed a new concept of impact reduction factor and a new method based on the developed concept, kinematics and the law of conservation of energy, [7]. The developed method yielded three algebraic equations, which provide estimates for the impact factors that develop as the train wheels travel over a descending track profile "$K_{B,d}$", a decreasing track stiffness transition "K_{B1}" and an increasing track stiffness transition "K_{B2}" [8, 9]. This paper presents the development of the fourth equation that estimates the impact factors, which develop as the train wheels travel over an ascending track profile "$K_{B,a}$". Currently, the proposed estimates exclude damping and consider linear-elastic track behaviour of the track only. The strong correlations of the estimates of the proposed method with the existing empirical equations are present in the author's earlier studies and therefore will not be repeated in this study [7, 8, 9].

2 Effects of track profile variation and track stiffness variation on the vertical impact forces exerted on the railway track

Fig. 1 shows two railway track profiles, along which the wheel of a train descend or ascend an amount equal to "h" over a rough length of track "L". The track stiffness "k" for these two cases is constant along the track and the only variable is the track profile. The static track deflection of the track in the first position of the wheel is "a". The dynamic track deflection of the track in the second position of the wheel is "c".
Fig.2 shows two railway track profiles along which the wheels transition from a region of high track stiffness to a region of low track stiffness, and from a region of low track stiffness to a region of high track stiffness. The stiffness at location 1 is k_1 and the stiffness at location 2 is k_2. Along the two tracks, the track profiles are initially level. The change of stiffness occurs along a rough track length of "L". The static track deflection of the track in the second position of the wheel is "b". The elevation difference of the tributary mass of the wheel due to a change in the difference between the static track deflections at locations 1 and 2 is "h".
In Fig. 1 and Fig. 2, the potential energy of the tributary mass "m" carried by the wheel changes as the wheel rolls along the rough length of the track due to the change in track profile and the track stiffness. As the wheel moves from location 1 to 2, they laterally move an amount of "L" and vertically move an amount of "h".

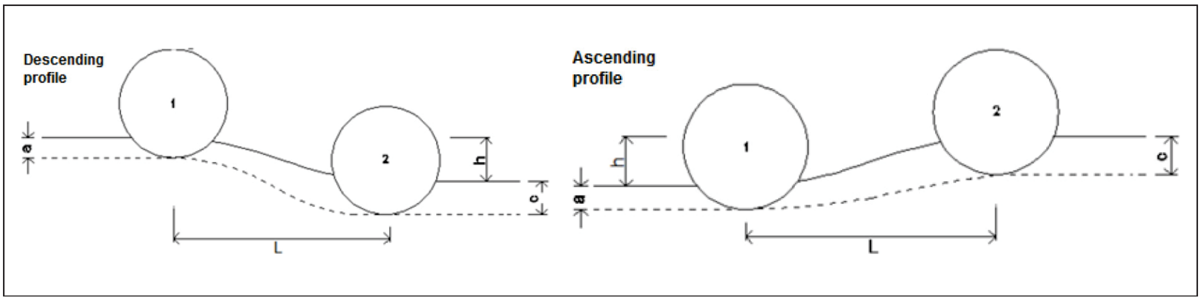

Figure 1 Sketches of maximum settlement envelopes for descending and ascending railway track profiles under a vertical wheel force along tracks with constant track stiffness, [7, 8]

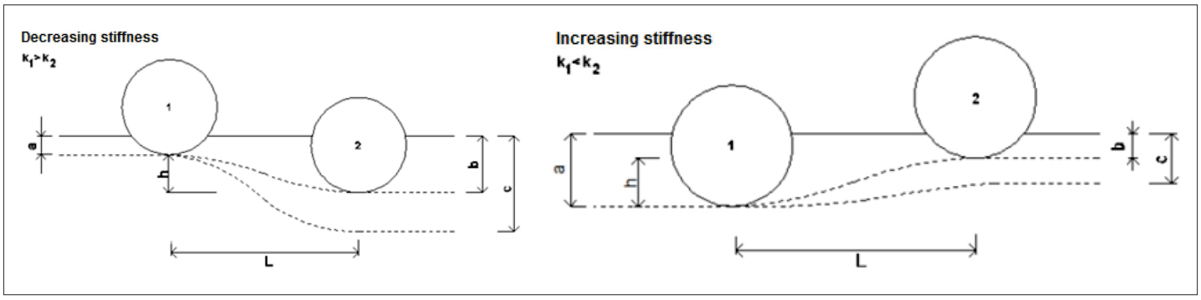

Figure 2 Sketches of maximum settlement envelopes for decreasing and increasing stiffness transitions along railway tracks, [9]

2.1 Impact reduction factor

The dynamic track deflection depends on the amount of the potential energy transferred into the track, which in return depends on the translational speed "v" of the wheel, the rough length of the track "L" and the vertical difference in profile "h". Eq. (1) reintroduces a new concept through a parameter "f" named by the author as the "impact reduction factor" [7-9].

$$f = 1 - \frac{t_{fall}}{t_{pass}}, \quad \text{where} \quad t_{fall} = \sqrt{\frac{2h}{g}} \quad \text{and} \quad t_{pass} = \frac{L}{v} \tag{1}$$

The degree of impact as the wheel rolls over the length of track that has a profile variation, relates to the time it takes for the wheel to hypothetically free-fall from vertical deviation height of "h", referred to as t_{fall} and the time to traverse the length of track "L" with profile variation, referred to as t_{pass}.

The impact reduction factor estimates the amount of the potential energy that transfers into the track as the wheels traverse the rough length of the track. The comparisons in Eqn. (2) present the possible impact reduction factor values [7-9].

$$\text{If} \quad \begin{Bmatrix} t_{fall} < t_{pass} \\ t_{fall} = t_{pass} \\ t_{fall} > t_{pass} \end{Bmatrix} \quad \text{then} \quad \begin{Bmatrix} 0 < f \le 1 \\ f = 0 \\ f < 0 \end{Bmatrix} \tag{2}$$

If the train speed is low and traverses the rough length of track in a long duration of time, the impact reduction factor approaches unity and therefore no-impact or very limited impact on the track takes place. If the train speed is high or the rough length of the track is low such that the wheel traverses the rough length of track in a short amount of time compared to the hypothetical time to fall from the vertical deviation that develops along this rough length, the impact reduction factor approaches to zero and full impact or high level of impact on the track takes place. Finally, if the track roughness varies abruptly within a very short length of track or the train speed is very high over a limited rough length of track, the impact reduction factor can fall below zero, indicating that the vertical wheel force is now acting on the track with an acceleration that is higher than the gravitational acceleration. Therefore, for a given “L” and “h”, the impacts increase with increasing speeds. For a given “L” and “v”, the impacts increase with increasing values of “h”.

2.2 Introduction of the Bezgin Method to estimate vertical impact forces

The proposed method by Bezgin, basis on the time based variation of the potential energy of the tributary mass of a train wheel as the train moves along the track. Fig. 3 provides a Cartesian representation of the varying track profile along the rough length of the track as the train moves along the x-axis in time. In this representation, y_0 is the elevation of the level-track when the train loads are absent from the track. Between the locations 1 and 2, the track profile ascends a vertical distance of “h”. Under the static wheel force, the track deflects an amount “a” at location-1. Based on the impact reduction factor, a part of this energy transfers into the track at location-2. This impact generates a higher track deflection of “c” at location-2. Therefore, the net variation in elevation is $\Delta = h - c + a$.

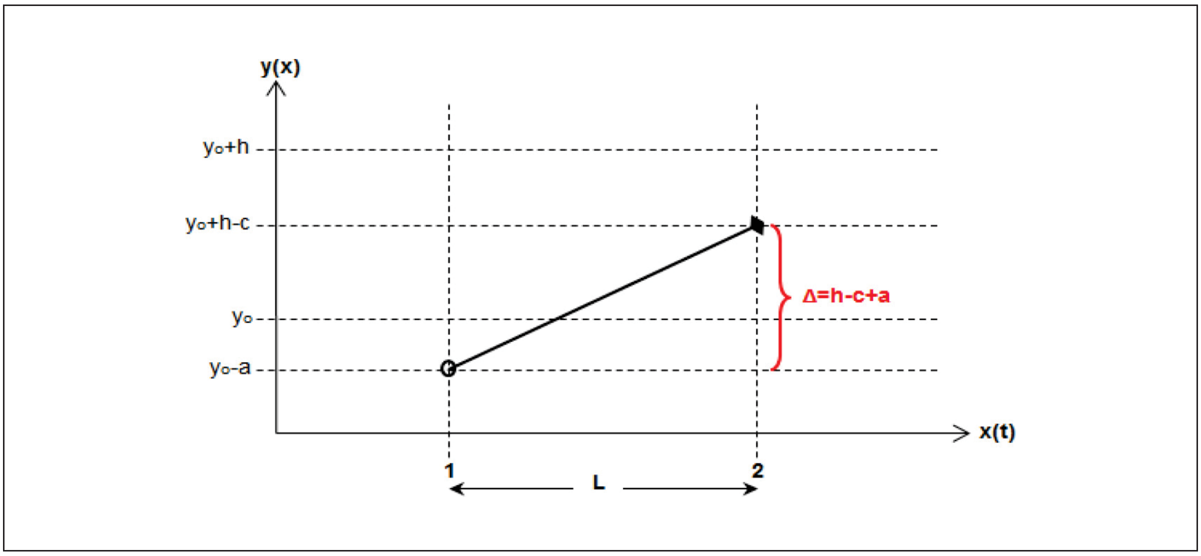

Figure 3 Cartesian presentation of the vertical variation of the ascending track profile along the rough length of track

Eq. (3) presents the part of the potential energy “E2” that transfers into the track at the location-2 depending on the impact reduction factor that occurs as the wheel rolls over the rough length of the track. E1 is the potential energy due to Δ.

$$E2 = m \cdot g \cdot (h - c + a) - m \cdot g \cdot h \cdot f \tag{3}$$

Eqn.4 presents the potential energy “E3” temporarily stored in the track due to an increase in the deflection from its static value to its impact value where k = m.g / a.

$$E3 = \frac{1}{2} k (c + a)(c - a) \tag{4}$$

Eq. (5) equates E2 with E3 by applying the principle of energy conservation and excluding energy dissipation via damping.

$$m\cdot g\cdot(h-c+a)-m\cdot g\cdot f\cdot h=\frac{mg}{2a}(c+a)(c-a) \tag{5}$$

Eq. (6) through (9) algebraically develop Eq. (5) and result in Eq. (10) that relates impact deflection “c” of the track to its static deflection “a”.

$$2\cdot a\cdot h-2\cdot a\cdot c+2\cdot a^2-2\cdot a\cdot f\cdot h=c^2-a^2 \tag{6}$$

$$2\cdot a\cdot h\cdot(1-f)+3\cdot a^2=(c+a)^2-a^2 \tag{7}$$

$$\sqrt{2\cdot a\cdot h\cdot(1-f)+4\cdot a^2}=\sqrt{(c+a)^2} \tag{8}$$

$$2\cdot a\cdot\sqrt{\left[\frac{h}{2a}\cdot(1-f)+1\right]}=c+a \tag{9}$$

$$c=a\cdot\left(2\cdot\sqrt{\left[\frac{h}{2a}\cdot(1-f)+1\right]}-1\right) \tag{10}$$

Eqn. 11 presents the impact force of wheel “F_i” related to its static force “F_s”.

$$F_i=k\cdot c=k\cdot a\cdot\left(2\cdot\sqrt{\left[\frac{h}{2\cdot a}\cdot(1-f)+1\right]}-1\right)=F_s\cdot\left(2\cdot\sqrt{\left[\frac{h}{2\cdot a}\cdot(1-f)+1\right]}-1\right) \tag{11}$$

The term in the parenthesis, presented in Eqn. (12) is the “Bezgin Impact Factor “$K_{B,a}$” due to ascending profile irregularity of the track”.

$$K_{B,a}=2\cdot\sqrt{\left[\frac{h}{2a}\cdot(1-f)+1\right]}-1 \text{ , for ascending track profile} \tag{12}$$

Eq. (13), (14) and (15) present the impact factor equations attained by the presented method for descending track profile and the decreasing and increasing stiffness transition conditions respectively [6, 7].

$$K_{B,d}=1+\sqrt{\frac{2h}{a}(1-f)} \text{ , for descending track profile} \tag{13}$$

$$K_{B1}=\left[1+1.414\sqrt{1-f+\frac{a}{b}\cdot(f-1)}\right] \text{ , for } k_1 \geq k_2 \text{ where } a \leq b \tag{14}$$

$$K_{B2}=\left[1.414\sqrt{1+f+\frac{a}{b}\cdot(1-f)}-1\right] \text{ , for } k_1 \leq k_2 \text{ where } a \geq b \tag{15}$$

3 Application of the introduced concept and the method

This section presents an application of the proposed equations for hypothetical rough track conditions. Fig. 4 presents the estimated impact factors for the descending and ascending track profile conditions respectively where the track stiffness per rail is k = 43 kN/mm for both cases. The vertical variation of track profiles are: h = 4 mm, h = 8 mm and h = 12 mm over rough track lengths of L = 10 m, L = 25 m and L = 70 m. The static axle force is F_s = 170 kN.

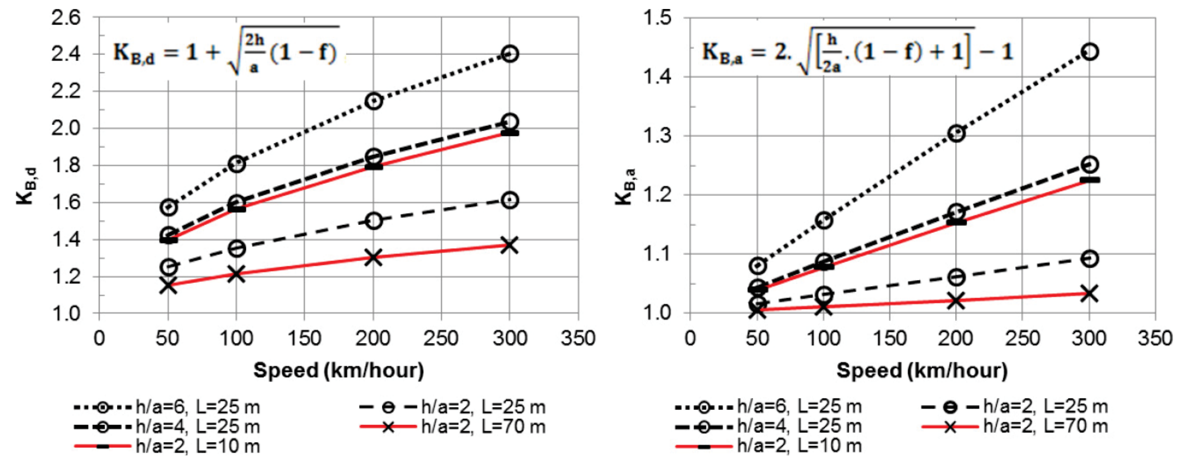

Figure 4 Estimation of the impact factors $K_{B,d}$ and $K_{B,a}$ by the proposed method for the descending and ascending track profiles

Fig. 5 presents the estimated impact factors for the decreasing and increasing stiffness transition cases for different values of "f". a / b = 0 represents a condition where the wheels transition from a region of infinite stiffness to a region of lower stiffness; a = b represents equal stiffness values and hence no impact.

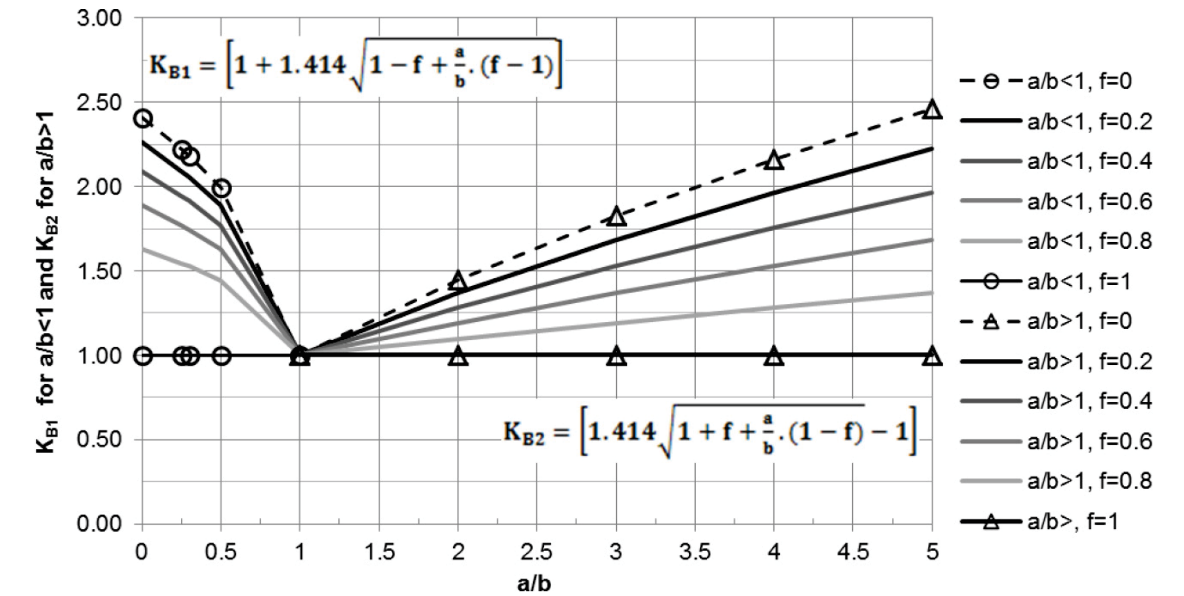

Figure 5 Estimation of the impact factors K_{B1} and K_{B2} by the proposed method for the decreasing stiffness ($k_1 > k_2$ and a / b < 1) and increasing stiffness ($k_1 < k_2$ and a / b > 1) transitions

4 Discussion of results and introduction of future work

Fig.4 shows that for a given speed, the impact factors increase with increased “h/a” values and decreased “L” values. Since “a” depends on the static wheel force the impact effect of a given “h”, “L” and “v” also depends on the static wheel force. Fig.4 also shows that the developing impact factors as the wheels roll-off a descending profile are higher than the values as they roll-on an ascending profile.
Fig.5 shows that there is a clear difference between the effects of an n-fold stiffness transition with respect to a $1/n^{th}$ stiffness transition where “n” is the ratio of stiffness values along the track transition. For a given value of “f” there are particular values of “a/b” where the estimated impact factors “K_{B1} and K_{B2}” are equal. Another interesting outcome is that there are maximum limits to developed impacts for “f” values as the wheel transitions from high stiffness to a low stiffness track. However, there is no clear limit to the increasing impact as the wheel transitions from low stiffness track to higher stiffness track.
This study summarized the current state of an on-going work. The findings up-to-date mathematically prove the variations of impact forces as the trains traverse ascending or descending track profiles and increasing or decreasing track stiffness transitions. The proposed method is advancing by the inclusion of damping and train suspension stiffness into the proposed equations and comparisons of their estimates with those of advanced simulation software and field measurements.

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