



ASSESSMENT OF DYNAMIC IMPACT FORCES GENERATED BY WHEEL FLATS: A COMPARISON OF ESTIMATES BY BEZGIN-KOLUKIRIK EQUATIONS AND MEASUREMENTS BY RUTE

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Abstract

Wheel flats are critical defects as they generate dynamic forces that can damage railway tracks and rolling stock components and also cause discomfort due to noise and vibrations. These damages may include wheel and rail cracks, fractures, and sleeper cracks. To mitigate such risks, various health monitoring systems have been developed to measure axle loads and determine the location and magnitude of wheel defects. These systems typically evaluate wheel–rail interaction and identify deviations from ideal wheel geometry. However, track instrumentation may not always be available, and the installation of such systems can be costly. Alternatively, analytical methods consistent with field measurements can provide estimates for different operational conditions. The Bezgin–Kolukırık equations provide insight into dynamic impact forces in relation to wheel flat geometry and key track and vehicle parameters. In this study, dynamic wheel forces measured by a wheel impact detection system developed by the Rail Transportation Technologies Institute were compared with estimates obtained from the Bezgin–Kolukırık equations. The consistency between the two approaches varied between approximately 50% and 175%. The results indicate that the analytical method captures the general trend, while deviations are correlated with wheel flat length, suggesting that defect severity significantly affects prediction accuracy.

Keywords: wheel flats, dynamic wheel forces, TUBITAK, RUTE, TCDD, OTMI, HATS, Bezgin Method, Bezgin-Kolukırık equations, wheel impact detection

1 Introduction

Wheel flats are critical defects of train wheels that can cause noise, vibration, and safety problems. During acceleration or braking, an imbalance in the longitudinal forces acting along the wheel–rail contact or the malfunctioning of the braking mechanism may cause the wheel to lock and slide along the rail. As a result, a local part of the wheel tread can be flattened and the wheel can deviate from its ideal circular geometry. Figure 1 shows an example of a wheel flat observed on a test train.

Wheel flats may cause significant damage to both railway vehicles and the track due to the high dynamic impact forces they generate. Such damage can include hot or broken axles and axle boxes, bearing failures, cracks propagating into the wheels [1], rail fractures that may lead to derailment, and cracking of concrete sleepers [2].

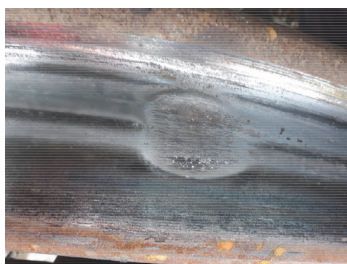


Figure 1 An example of a wheel flat

The vertical dynamics and vibration behavior of cars with wheel flats have been extensively studied in the literature [3-5]. Additionally, the development of defects and the factors contributing to their formation have been investigated by various researchers [6, 7].

Various condition monitoring systems have been developed to measure dynamic impact forces resulting from the interaction between the wheel and the rail. Examples include the DafuR [8] in Germany and the GOTCHA [9, 10] (optical fiber-based wheel-flat detection and axle load measurement system) in the Netherlands. By applying strain gauges to the rail, the wheel-rail contact response during a train passing through the instrumented area can be measured. It is also possible to use load cells to determine the axle loads, while optical sensors and accelerometers can be employed to detect wheel defects. Wheel impact load detectors – WILD – quantify impacts either as the force generated at the wheel-rail interface or as an index indicating the severity of the defects [11]. The data provided by the monitoring systems can be used specifically to detect out-of-round wheels. For example, the GOTCHA system measures multiple parameters, including the wheel force of a passing train. The obtained data are later used in the Gotcha alarm system, where the condition of the wheels is monitored and a score for the defect level is rendered based on an algorithm [12].

This study presents the HATS, which is a new measurement module currently under development, within an array of modules that compose the track and rolling stock health monitoring system – OTMI – developed by the Rail Transportation Technologies Institute (RUTE). The system can detect the location of wheel flats and the dynamic impact forces generated by them. OTMI was developed as part of an ongoing effort to enhance and support the needs of the modernized Turkish railway network as well as the needs of Eastern European, Middle Eastern, and Western Asian railway networks. OTMI was developed at RUTE, which was established in 2019 as part of an agreement between the Scientific and Technological Research Council of Turkey – TÜBİTAK – and Turkish State Railways – TCDD. As an alternative means of measurement, dynamic impact forces can also be estimated using analytical methods. The Bezgin-Kolukırık equations are a validated set of equations that estimate dynamic impact forces due to wheel flats through force factors $K'B3$ and $K'B3$, H . These equations are based on the Bezgin Method, developed to estimate dynamic impact forces due to track and wheel irregularities. Wheel impact detection typically concentrates on the forces generated by wheel flats and not on the particular length of the wheel flat that generates the forces. From the railway managers' perspective, the wheel that generates forces beyond a certain threshold is removed from operation and tried to proper circularity before it is accepted back into service. From a scientific point of view, the direct relation between the dynamic impact forces and track stiffness, rolling stock stiffness, wheel diameter, and wheel flat length is of importance.

This study compares the dynamic impact forces measured by RUTE's monitoring systems, as part of trial and calibration tests, with the estimates obtained from the Bezgin-Kolukırık equations. Furthermore, the relationship between the measured and estimated dynamic impact forces and various wheel flat lengths is examined.

2 Wheel flat measurement system – Hızlı Apleti Ölçüm sistemi (HATS)

HATS is a track-based inspection system that collects wheel data from in-service trains using load sensors installed on the track and runs an inspection algorithm on this data to detect whether there is a wheel flat and, when detected, determine its magnitude, depth, and location within the train consist. The system uses fiber optic sensing technology to derive the load distribution along the wheel tread by creating a measurement zone on the railway track corresponding to the wheel circumference. There are two axle counters located immediately to the east and west ends of the seven consecutive load sensors. These axle counters magnetically detect wheel presence and have two attached windings enabling them to measure the speed of each wheel as well. With the use of axle counters, precise positioning of the wheel within the measurement zone enables adjustable load superposition. In addition to wheel flats, the system can also provide axle loads, unbalanced loading, and wagon weights based on its automatic calibration capability enabled by the integrated train identification system. Figure 2 is a representative image of the system and figure 3 shows the field application.

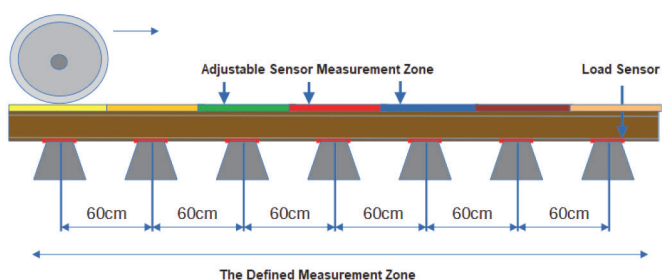


Figure 2 A representative implementation of HATS



Figure 3 The field application of HATS

Figure 4 presents a representative E68000 series locomotive of the same type used in a test. This locomotive has a BoBo wheel arrangement consisting of two bogies with two axles each.



Figure 4 A representative locomotive from the E68000 Series [13]

By means of fiber sensing and proprietary wheel data generation algorithms, highly stable wheel data are obtained, enabling lower false alarm rates. In addition to flat spots, wheel surface defects can also be detected. Furthermore, the system is capable of performing accurate wheel load measurements through automatic calibration enabled by an integrated identification system.

3 Bezgin–Kolukırık equations

Bezgin Method [14, 15] is an energy-based method that is applicable to any track or wheel roughness conditions where dynamic impact forces can occur. The application of this method to wheel flat case yielded the Bezgin-Kolukırık equations [16-18], presented in equation (1) and (2). The geometric conditions considered for the evaluation of the wheel flats is presented in figure 5.

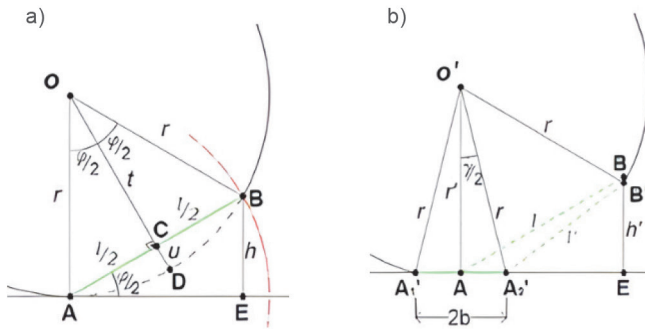


Figure 5 The geometry of a wheel flat a) without considering and b) by considering Hertzian contact flattening [19]

The parameters used in the equations are wheel flat length (l), train speed (v), static deflection of the combined track and vehicle system under the static wheel load (a'), angular speed of the wheel (φ), wheel radius (r), the gravitational acceleration (g), the flattening width at the wheel–rail contact interface ($2b$), the drop height caused by the wheel flat without considering Hertzian contact deformation (h), the drop height considering Hertzian contact flattening (h').

$$K'_{B3} = 1 + 2 \cdot \sin \frac{\varphi}{2} \cdot \sqrt{\frac{2 \cdot l \cdot v}{d \cdot \varphi \cdot \sqrt{r \cdot g}}} \quad (1)$$

$$K'_{B3,H} = 1 + 2 \cdot \sin \frac{\varphi}{2} \cdot \sqrt{\frac{2 \cdot l \cdot v \cdot \left(\frac{H'}{h}\right)}{d \cdot \varphi \cdot \sqrt{r \cdot g}}} \quad (2)$$

In this study, Hertzian contact flattening was excluded to avoid complications in the comparisons between the measurement results and the analytical predictions. Therefore, the analytical calculations were performed using equation (2).

4 Comparison of the estimations and measurements

The RUTE - HATS track measurement dataset contains dynamic measurement data obtained from sensors instrumented in the track. These data include wheel load, maximum wheel force, and average load. The dynamic impact force factor (K'_{B3}) based on wheel flats was calculated using the primary and secondary suspension spring stiffness (k_w and k_b), track stiffness (k), Hertzian contact stiffness (k_H), wheel diameter (D), and train speed (v) parameters. These values are considered to be $k_w = 10$ kN/mm, $k_b = 5$ kN/mm, $k = 60$ kN/mm, $k_H = 20,000$ kN/mm, and $D = 1020$ mm. Axle speed, average wheel load on the axle, and axle length were obtained from the HATS sensor data. Accordingly, a comparison of the maximum/average axle load ratio of the test train with the K'_{B3} dynamic factors is shown in figure 6.

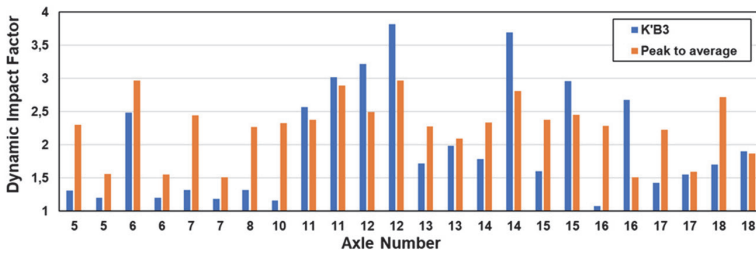


Figure 6 The comparison of the dynamic impact factors obtained from the Bezgin-Kolukirik equations and field measurements

$K'_{B,3}$ values varies between approximately 47% and 177% of the dynamic force ratio obtained from the sensors. The consistency between these two dynamic impact factors appears to be related to the wheel flat length. As shown in figure 7, when the wheel flat length is less than 36 mm, the K'_{B3} factor is lower than the force factor obtained from the sensors. Conversely, when the wheel flat length exceeds approximately 59 mm, the K'_{B3} factor reaches higher values than the force factor measured by instrumentation. When the wheel flat length is between 36 and 59 mm, the consistency between the estimations and measurements is higher.

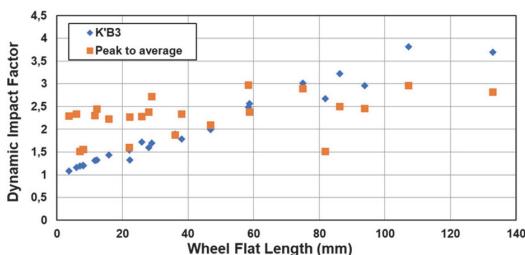


Figure 7 The relationship between dynamic impact factor and wheel flat length

In figure 8, the ratio of dynamic impact forces estimated by the analytical method to the measurements in an instrumented track is shown depending on the wheel flat length. The line of equality indicates the points at which the analytical estimates and sensor measurements coincide. As the data points deviate from this line, the discrepancy between the two approaches increases accordingly.

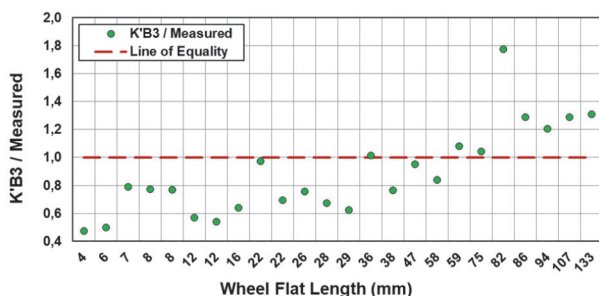


Figure 8 The relationship between the estimated / measured dynamic factors and wheel flat length

Figure 9 also illustrates the relationship between the measured and estimated dynamic factors due to wheel flat. Most data points fall above the line of equality, showing that measured forces are generally higher than those estimated analytically. All dynamic impact factors corresponding to wheel flat lengths below 36 mm fall within this region. However, when the wheel flat length exceeds 59 mm, the measured impact forces become higher than the estimation results.

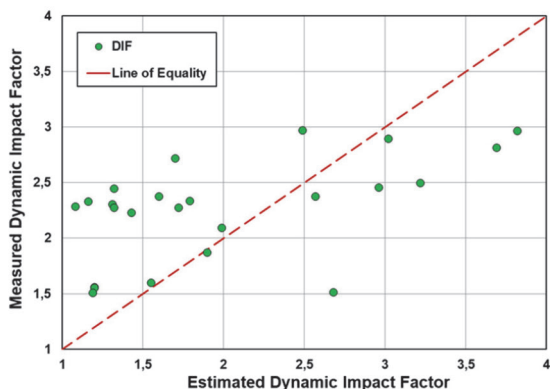


Figure 9 The relationship between measured and estimated dynamic impact factors

In order to interpret the results properly, it is necessary to discuss the scientific frameworks of HATS and the Bezgin-Kolukirik equations. The equations estimate the dynamic forces at the wheel–rail contact point based on the law of conservation of energy, rules of kinematics and a function for the transfer of impact energy in time. HATS measurements, on the other hand, are performed using fiber optic sensors installed along the rail at intervals of 60 cm. The evaluation is based on the force-time signal recorded as the wheel with a flat passes over the sensors. The width of the dynamic force peak observed in the sensor data provides information about the severity and characteristics of the wheel flat. When the wheel-rail contact point of the flat is close to the sensor, this peak can be captured more distinctly; however, as the contact point moves farther away from the sensor, the measured peak value becomes attenuated. Therefore, mathematical formulation is used to eliminate the effect of measurement location, allowing a position-independent assessment of wheel flat length.

The Bezgin-Kolukirık equations can estimate dynamic forces for a static wheel load by accounting for mass distribution among the wheel, bogie, and car body when their masses are known. Sensor-based measurements, on the other hand, produce different force-time responses for different static wheel loads. As the static wheel load increases, increased wheel-rail contact deformation may lead to an effective extension of the force-time interaction, causing the measured force distribution to spread over a wider time interval. Therefore, relevant sensor data parameters are corrected to eliminate the influence of wheel load, allowing a generalized assessment of wheel flat length. Finally, both approaches take train speed into account. As train speed increases, the wheel flat impacts the rail with higher angular velocity. With increased velocity, the contact duration also decreases, which may lead to a lower transfer of energy. This effect is reflected in the force-time signals obtained from the sensors. While the analytical approach estimates the peak force at the wheel-rail contact point based on multiple parameters, HATS provides an estimation based on the width of the impact caused by the wheel flat in the force-time signal. Consequently, a wheel flat length of approximately 59 mm emerges as a threshold value in terms of the ratio between analytical and measured results, indicating a transition in the dominant interaction characteristics captured by the two approaches. As a measurement system, HATS has the inherent advantages of capturing the results of an implicit array of mechanical and kinematic effects. Like its predecessors, HATS aims to capture the effects of wheel flats and support a proactive maintenance protocol that identifies the wheels with flats and their locations, which generate forces exceeding thresholds. However, the HATS algorithms and sensor architecture have the added advantage of assessing the length of wheel flats, which can aid the assessor in correlating the effects of wheel flats in relation to wheel diameters.

5 Conclusion

The comparison of HATS measurements with the Bezgin-Kolukirık equation estimations showed that wheel flat length is a significant factor influencing the level of agreement between the two approaches. Measured wheel loads were higher than the estimated loads when the wheel flat was less than 36 mm. Conversely, the measured loads fell below the estimated values for wheel flat lengths exceeding 59 mm. These results suggest that the analytical approach tends to be more conservative for larger wheel flat conditions. The two methods showed better consistency when the wheel flat changed between 36 mm and 59 mm. Overall, the ratio of the dynamic impact factors obtained from the two methods varied between 47% and 177%.

The loads obtained from wheel impact detection systems are commonly compared against predefined threshold values to assess defect severity and to support maintenance decision-making. However, incorporating detailed track and train parameters into the evaluation process can provide deeper insight into their influence on dynamic impact forces when interpreted through analytical methods. In the present study, wheel load data measured by the sensor system were available and therefore used for comparison, whereas several track and vehicle parameters had to be represented by assumed values. A one-to-one comparison using the exact parameters recorded during measurements would enable more realistic and consistent evaluations. The effect of wheel flats in relation to wheel diameter is a very important issue, as the effect of a given wheel flat will change with respect to wheel diameter. Currently, HATS is an installed system along commuter and inter-city railway tracks. Ongoing efforts concentrate on developing a mobile version of HATS that can capture the effects of wheel flats along urban railways, which operate trains with lower wheel diameters and a significantly different operational regime. Future studies will further improve the reliability of such comparisons by integrating comprehensive track and vehicle parameter data from instrumented measurements into the analytical modeling framework.

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