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Simulation of a Freight Train and The Effect of Wheel Flat Defect on The Wheel/Rail Dynamic Forces

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Abstract: Wheel/rail interaction is one of the most important research topics in railway engineering and generally includes impact response, vibrations, and track safety. Track structure failures caused by wheel/rail impact dynamic forces can lead to significant economic loss through damage to rails, ballast, fastening system, etc. Wheel/rail impact forces occur due to defects in wheels and/or rails such as wheel flats, irregular wheel profiles, rail corrugation, etc. A wheel flat can cause a large dynamic impact force as well as high frequency forced vibrations, which will eventually lead to damage to the train and track structure. In the present work, a freight train (3D model) was used to analyze the dynamic impact caused by the wheel flat using UM software. The effects of wheel flat depth and length (0, 0.2, 0.5, 1, 1.5, 2, and 3 mm) at two speeds of 50 and 80 km/h on wheel/rail dynamic forces have been investigated. The results showed that the presence of a wheel flat defect significantly increases the wheel/rail dynamic impact. For example, by increasing the wheel flat depth to 3 mm, the values of maximum force at speeds of 50 and 80 km/h have changed by about 235% and 400%, respectively.

Keywords: Freight Train, Railway Vehicles, Simulation, Wheel Flat Depth, Wheel Flat, Wheel/Rail Force

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Research paper

1 INTRODUCTION

The existence of a geometric defect in the interaction between the rail and the wheel is one of the sources of the dynamic interaction of the train. Wheel profiles have a significant effect on the safety and dynamic performance of the vehicle; For example, in terms of the dynamic stability of the vehicle, the magnitude of the wheel/rail contact forces, and/or ride comfort. Wheel tread defects are usually divided into two main categories: (i) defects along a portion of the wheel circumference and (ii) defects around the entire wheel. Both mentioned defects are considered types of wheel out-of-roundness (OOR) phenomena. The first group includes wheel flat, shelling, spalling, etc., and is mainly caused by braking damage and rolling contact fatigue cracking. The second category includes corrugation of the wheel and polygonal wheel (due to non-uniform wear), which are periodic irregularities around the wheel that can be caused by unbalanced loads. The non-roundness of the railway wheels has an undesirable effect on the components of the track and the railway vehicle. In recent decades, some researchers have focused on the methods of diagnosing and analyzing the dynamic behaviour of the train due to wheel flat [1-12]. When the wheel-set is locked and slides along the rails as a result of improper or defective brakes, wheel flat occurs. Therefore, the surface of the wheels becomes flat instead of round due to the friction between the wheels and the rails. Wheel flats create high dynamic impact loads on railway substructure, which cause significant damage to rail and track vehicles. Among these damages, we can mention broken axles, hot axle-boxes, damaged rolling bearings, and cracks in wheels, rails, and ballasts. In addition, this type of wheel defect causes excessive noise and vibration. These large vibrations are transmitted to the rolling stock and by applying and inducing excessive forces (more than the permissible values), they cause damage to the suspension systems, bogie frame, and body of rail vehicles. In addition, wheel and track irregularities can lead to improper performance of the train and overhead track interaction. Therefore, in order to deal with this issue, railway centers generally carry out the necessary measures and monitoring. As a precaution, most passenger trains are now equipped with advanced anti-slip systems that slightly reduce wheel/rail slip. However, with increasing operating speeds and axle loads, wheel flatting cannot be completely avoided. In addition, since freight trains do not have anti-slip systems, the condition of the wheels is usually worse and has a significant impact on the useful life of the trains and substructure [13-29].

In recent years, various researchers have studied the field of wheel flat defects (causes, solutions to reduce defects, maintenance, and railway vehicles monitoring), among which can be referred to Bosso et al. [17], Mishra et al. [18], Chen et al. [19], Ng et al. [20], Wang et al. [21], Sattari et al. [22], etc. Bosso et al. [17] used an algorithm in the time domain to detect wheel flat defects (early stage and to estimate the severity) by measuring the vertical acceleration on the axle-box. Mishra et al. [18] presented the real-time implementation of fiber Bragg grating sensors on rail tracks and investigated the train's wheel flat status (passenger train running at a speed 70 kmph). Chen et al. [19] assessed wheel conditions in high-speed trains under various operational conditions. Ng et al. [20] studied the association between wheel flat, wheel/rail impact responses, and vibration signals (a 3D finite element model). Wang et al. [21] investigated the axle-box vertical vibration caused by wheel flat in the conventional time and frequency domain by modeling a high-speed railway system (94 degrees of freedom with wheel flat defect). Sattari et al. [22] studied the dynamic and safety of a freight train with wheel flat when passing through turnouts. Their results showed that the depth of the wheel flat, as well as the train speed, strongly affect the dynamic forces and derailment coefficient at the turnout.

Train wheels, among other components, are critical for the safety and ride comfort of railway systems. Various methods have been used to assess the wheel health conditions. In this paper, dynamic simulation is used to determine the effect of two basic parameters of wheel flat depth and train speed on wheel/rail dynamic forces, which is rarely presented in other research. In the current paper, first, the modeling of a freight train is done in the Universal Mechanism (UM) multi-body software, and then the effect of the depth and length of the wheel flat on the vertical force of the wheel/rail is evaluated. Investigations were carried out from the depth of the wheel flat from 0 to 3 mm (up to a length of 168 mm) at two speeds of 50 and 80 km/h and on a straight route.

2 RAILWAY SYSTEMS

The structural structure of the railway can be considered as consisting of two main parts: superstructure and substructure. What is generally referred to as the superstructure of railway tracks consists of the sleeper, fastening system, ballast, and sub-ballast layers (or other alternative components in different types of slab tracks), which provide a suitable platform for the train to pass. In general, and in terms of structure, the types of the superstructure in railway tracks can be classified into two general groups: ballasted and slab track. According to the conditions of the route and technical and economic studies, both types of these tracks can be used. In “Fig. 1”, a sample of ballasted tracks in Iran and Gaduk railway station (Tehran-Mazandaran route) can be seen. The use of ballasted tracks is widely used in Iran's railway tracks and due to their lower construction cost and taking into account all their advantages and disadvantages, it has an acceptable performance overall [30-36].

Fig. 1 Train-track system and considered bogie.

3 MODELING (TRAIN AND WHEEL FLAT)

To simulate a freight train, a three-piece bogie type 18-100 used in the countries of America, Russia, China, Canada, India, Australia, Brazil, and Iran has been used. Generally, simulations of three-piece bogies are based on models of a wedge friction system. The inertial properties of the wedges have been ignored and the linear model of tangential contact forces has been used. Some researchers used this train model for dynamic simulations. After completing the simulation of the dynamic characteristics of the train in the UM input section, the UM simulation section has been used to simulate the dynamic behavior of the system. Figure 2 shows a diagram of the simulated model, including the body, bogie, and its components, as well as the wheel/rail force. Generally, 3-piece bogies simulations are based on models of a wedge frictional system. The inertia properties of wedges are ignored and the linear model of tangential contact forces is used. The bogie has rigid contacts between the side frame and axle-boxes, car-body and bolsters in the center plate and side bearings including clearances, between frictional wedges and bolster or side frame. Hertzian solution and FASTSIM algorithm by Kalker as well as a modified non-elliptic multipoint contact model are used. To provide more details about the simulation, refer to references [22-24], [29-31], [37-38].

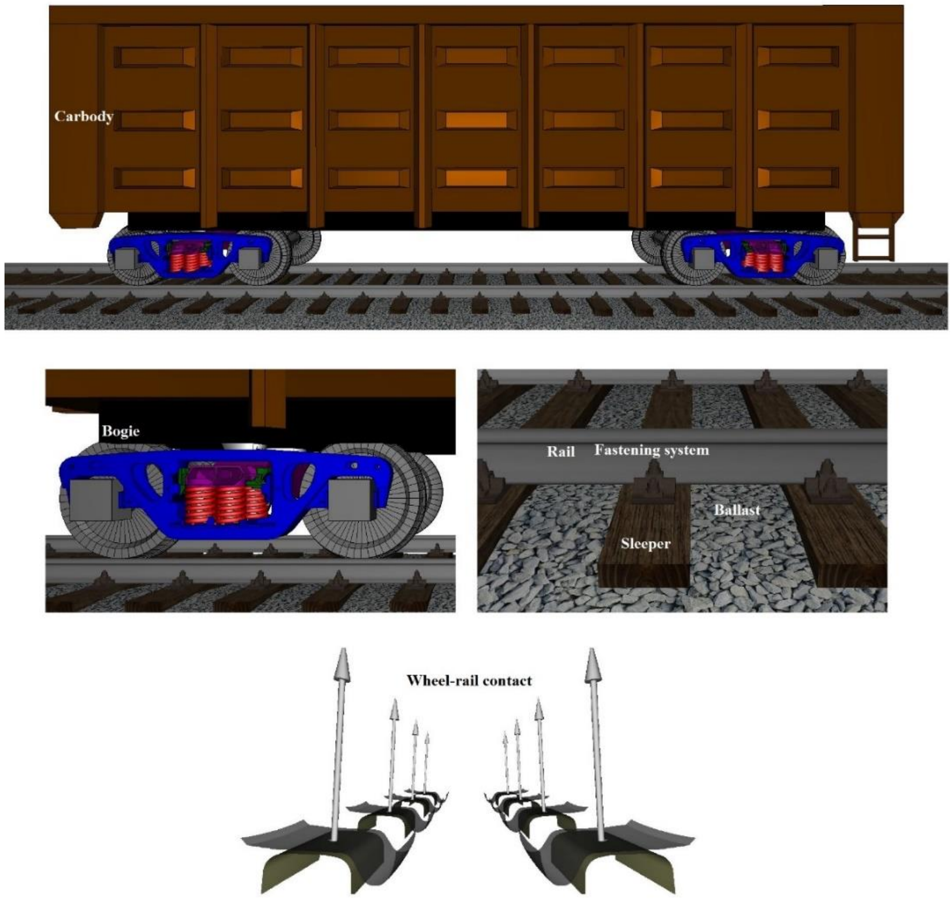

Fig. 2 Freight train modeled in UM software and its component.

The wheel flat defect generally occurs in two ways and a schematic of these two can be seen in "Fig. 3". In "Fig. 3 (a)", the wheel flat is rounded and in "Fig. 3 (b)" the wheel flat is deformed with smooth areas and sharp points (newly formed) [22-23], [39-44]. In this research, dynamic forces have been extracted from the wheel flat defect in the rounded state ("Fig. 3(a)") and at different depths.

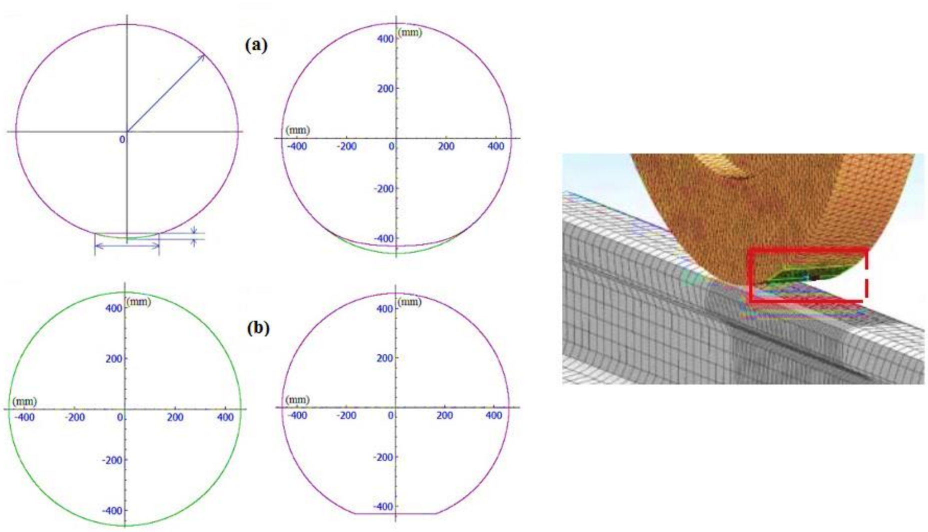

Fig. 3 Wheel flat defects in the form of: (a) rounded and (b) newly formed.

4 RESULTS AND DISCUSSION

Researchers with a field study of vibrations and train-track interaction have a great desire to obtain the values of wheel/rail forces considering different conditions of track and train. Today, the available methods for calculating wheel/rail dynamic forces are divided into two direct and indirect methods. In direct methods, the internal reactions of the wheel or train (including shear and bending moments, acceleration or displacement) are measured, which are directly related to the dynamic force of the wheel/rail.

There are many indirect methods, and among them, it is possible to measure the response of the train on the wagon body, bogie frame and axle-box of the train passing the track to calculate the dynamic force of the wheel/rail. These methods are more flexible, as trains can be equipped at stop times. Also, the use of software such as MATLAB, ABAQUS, UM, ANSYS, etc. to simulate railway systems and extract wheel/rail dynamic forces is interesting for researchers (indirect method). Today, with the increasing speed of trains, the growth of freight train loading and the variety of working conditions, the comprehensive study of wheel and rail dynamics is becoming more and more important [22-24], [30-33].

The bogie of the freight wagon has three main components, namely the wheelset, the bolster, and the side frame. In Iran, the widely used wagon bogie is shown in “Figs. 1 and 2”. The single-section freight wagon is mainly composed of one car-body and two bogies. Each group of bogies includes two wheelsets (including axle-boxes), two side frames, one bolster, and two suspension systems (114 DOFs). The car-body and bogie are rigid bodies with mass and they are assumed to move at a uniform speed along a straight railway line. The dynamic balance equation of a freight car can be expressed by the following formula (“Eq. (1)”):

$$\ddot{U}_{fw} + C_{fw}\dot{U}_{fw} + K_{fw}U_{fw} = f_{wr} \tag{1}$$

Where, M_{fw} is the mass matrix of the freight wagon, C_{fw} and K_{fw} are the damping and stiffness matrices of the freight wagon, respectively, $\ddot{U}_{fw}$, $\dot{U}_{fw}$, U_{fw} are the acceleration, velocity, and displacement vectors of the freight wagon, f_{wr} is the vector of the wheel/rail contact force [29].

The wheel flat is mainly characterized by the wheel flat length (L) and the flat depth (D), calculated according to Equation (2):

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

In which, r_w is the radius of the wheel. Also, the wheel flat vertical profile deviation (Z) is defined as (“Eq. (3)”):

$$Z = -\frac{D}{2}\left(1 - cos\frac{2\pi x}{L}\right)H(x-(2\pi r_w - L)), \quad 0 \le x \le 2\pi r_w \tag{3}$$

In which, H is the Heaviside periodic function, and x is the coordinate aligned with the track longitudinal direction. When a defective wheel rotates, the flat of the wheel causes a periodic impulse to the track with a particular frequency. The frequency of the periodic impulse corresponding to the flat impact frequency (f_f) can be determined as follows (“Eq. (4)”):

$$f_f = \frac{V}{2\pi r_w} \tag{4}$$

In which, V is the train speed [22-23], [27-28].

Figures 4 and 5 show the effect of wheel flat depth on wheel/rail vertical dynamic forces in a freight train with a speed of 50 and 80 km/h, respectively. The results show that with the increase in the depth of the wheel flat, the wheel/rail forces have increased significantly and it is consistent with the results of other researchers [39-44]. As can be seen in “Figs. 4 and 5”, the wheel/rail vertical force fluctuates in the range of 115 kN in all wheels of the train in the state without wheel flat defects (“Figs. 4 and 5 (a)”). However, by applying the defect and increasing the wheel flat depth and the speed of the train, these values show a significant increase. The results of the studies by Masilo et al. [39], Pringer et al. [40], Mosleh et al. [41], Spiro et al. [42], Bayan et al. [43], and Newton et al. [44] also show that with increasing the wheel flat depth, dynamic forces have increased.

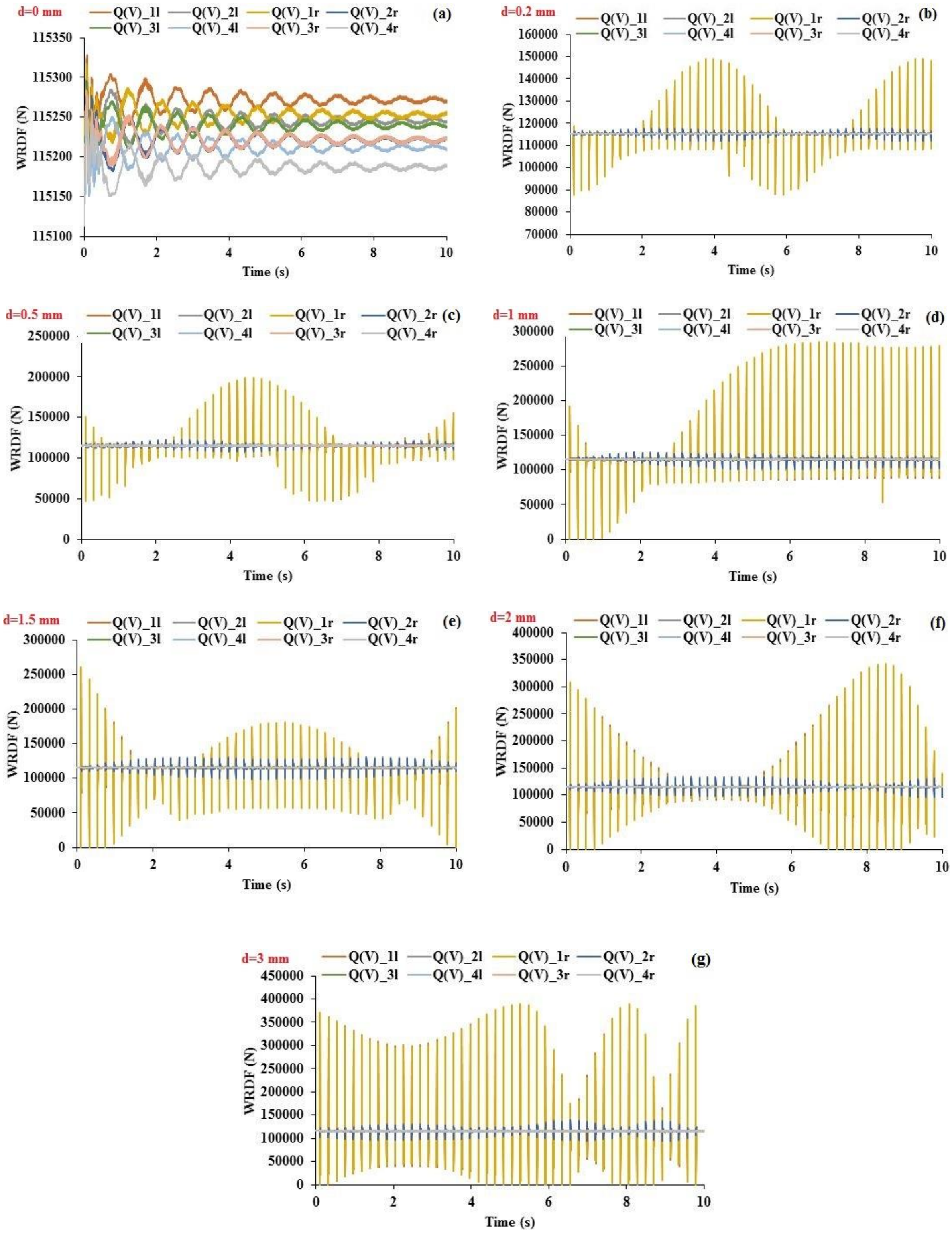

Fig. 4 Wheel/rail dynamic force at a speed of 50 km/h and in the wheel flat with different depths: (a): 0, (b): 0.2, (c): 0.5, (d): 1, (e): 1.5, (f): 2, and (g): 3 mm.

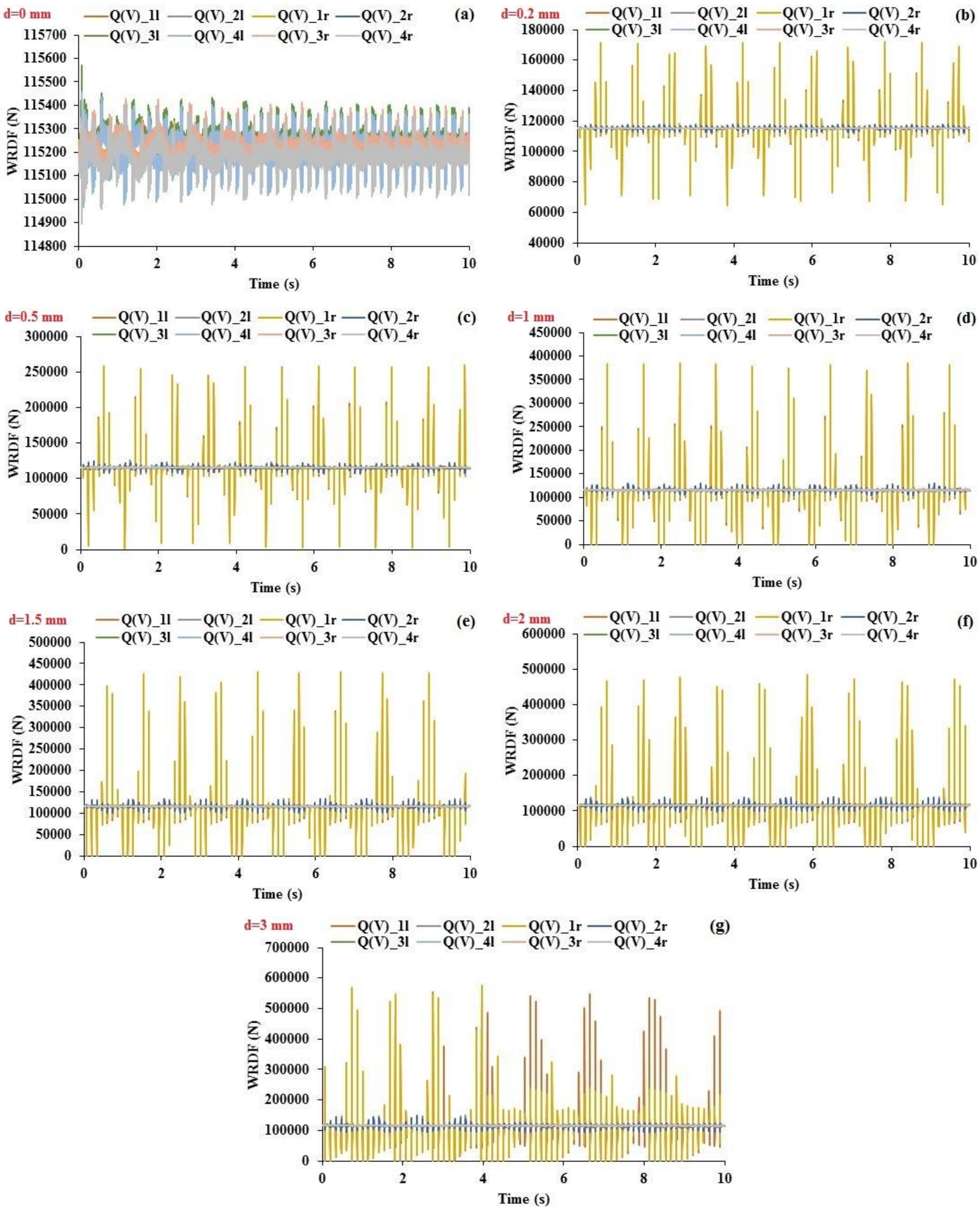

Fig. 5 Wheel/rail dynamic force at a speed of 80 km/h and in the wheel flat with different depths: (a): 0, (b): 0.2, (c): 0.5, (d): 1, (e): 1.5, (f): 2 and (g): 3 mm.

Figure 6 compares the wheel/rail dynamic forces (maximum and minimum values) at different depths of the wheel flat and different speeds. The results show that the wheel flat depth and train speed are two important factors in estimating the wheel/rail dynamic forces. The results of the studies by Spiro et al. [42] and Wall et al. [45] also showed that with the increase in train speed, the wheel/rail dynamic forces increased and it is in accordance with the current research. By increasing the wheel flat depth at a constant speed, the dynamic force is increased. For example, by increasing the wheel flat depth to 3 mm, the values of maximum force at speeds of 50 and 80 km/h have changed by about 235% and 400%, respectively. Also, by increasing the speed of the train at a wheel flat depth, the dynamic forces have increased. For example, at speeds of 50 and 80 km/h and a wheel flat depth of 1 mm, the maximum force values change by about 37%.

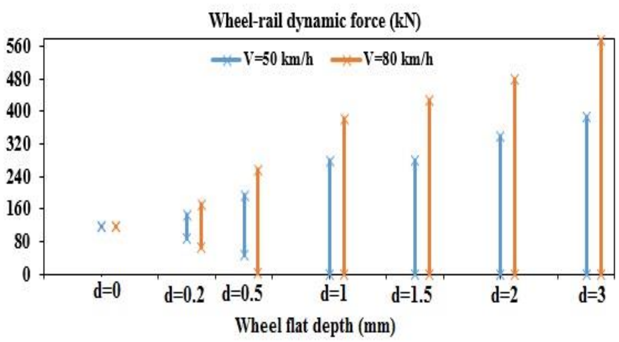

Fig. 6 Effect of train speed and wheel flat depth on wheel/rail dynamic force.

5 CONCLUSIONS

Calculation and estimation of wheel/rail dynamic forces can be done directly and indirectly. In this research, UM multi-body dynamics software was used for modeling, simulating, and extracting dynamic forces (indirect method). A common freight train in many countries was modeled with an 18-100 3-piece bogie, and then the effects of two parameters of train speed and wheel flat depth on wheel/rail dynamic forces were evaluated. Wheel flats are a key source of issues in railway systems, as they generate significant wear on both the infrastructure and the train carriages.

They can cause serious damage to the train and accidents, so identifying worn wheels is critical for human safety and rail transit. The results showed that both mentioned parameters are highly effective in estimating the forces and influencing them. By increasing the wheel flat depth at a constant speed, the dynamic forces of the wheel/rail have increased dramatically. Also, by comparing the changes in the train speed in a certain wheel flat depth, an increase in dynamic forces has occurred. For example, in the wheel flat depth of 0.2 mm, with the change of train speed from 50 to 80 km/h, the maximum value of vertical wheel/rail forces has changed by about 16% from about 147 to 171 kN.

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