Rail vehicle model motion analysis on curved track with vertical irregularity

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Abstract. The properties of a classic railway track largely depend on the properties of the subgrade, which is most often a natural creation. Atmospheric phenomena (e.g. temperature changes, heavy rainfall) can locally reduce the elasticity of the subgrade and create conditions conducive to permanent track deformation. One of the most common forms of a track fragment destruction is the loss of foundation support (one or several neighbouring sleepers) resulting from the indentation of the ballast material in the subgrade. The pressure of a vehicle passing through a damaged section of the track causes the so-called dynamic track irregularity. The impact of dynamic track vertical irregularity on the values of wheel-rail contact forces of a passing vehicle was investigated. The model of the passenger wagon-track system was created using the VI-Rail tool. The vehicle motion on curves with different values of track radius and superelevations was investigated. Vertical track irregularities occur on the internal rail only. The lengths of the track irregularity correspond to one, two or three sleepers unsupported on one side. The test results are presented in the form of diagrams and referred to applicable standards and regulations.

Keywords: track irregularity, numerical simulations, safety of motion criterion

1. Introduction

Railway infrastructure is exposed to the influence of all atmospheric and environmental factors occurring at its place of location. The essential requirement for infrastructure elements and constructions is to preserve the projected properties for foreseeable changes in atmospheric conditions. However, atmospheric phenomena occur that have not been reported previously (e.g. heavy rainfall). As a result of plant expansion, the track drainage system is also undergoing constant degradation. The coincidence of the abovementioned factors can lead to a temporary accumulation of rainwater in the subgrade and a decrease in its elasticity (fig. 1). The pressure caused by a passing vehicle causes the ballast under the sleepers to be forced into the softened track subgrade and rail deflection with sleepers in the vertical direction. So-called dynamic track irregularity is created. Parameters of it depend on the length of the track section on which the sleepers have lost support, the vehicle...
weight, rail stiffness and others. Investigating the impact of such irregularity on wheel-rail contact forces and relating them to the safety of motion criteria is the subject of this article.

Fig. 1. One side loose of slipper's support: a) real view, b) the modelled vertical irregularity as a result of vehicle negotiation (source: own elaboration)

The investigations presented below were performed on a curved track. A characteristic feature of the track situated on a curve is the track superelevation $h$ [1, 10]. Depending on the curve radius, it ranges from 50 to 150 mm. It is therefore evident that the accumulation of rainwater will first cover the internal rail of the track (inner side of sleepers) located 50 ... 150 mm lower than the external rail. Therefore, on the inner side of the track, conditions favourable to the occurrence of dynamic track irregularity will occur first, whereas the exterior tracks side may be correct. That's why the impact of the appearance of the internal track vertical irregularity on wheel-rail contact forces was investigated. Dynamic track irregularity is the only irregularity occurring on the studied track section. The values of wheel-rail contact forces are expressed as a function of tested vehicle motion velocity negotiation through the irregularity. The maximum values appearing in individual motion simulations were recorded. Then these forces were compared with applicable standards, regulations and recommendations [2, 8, 9, 11, 12].
2. The aim and scope of research

The purpose of the tests performed is:
− assessment of the impact of one side vertical track irregularity appearing on wheel-rail contact forces,
− checking, whether passing through such a bump may lead to non-compliance with rail vehicle safety of motion criteria.

Simulation tests were carried out on the curved track of a circular arc character with radii and superelevation listed in table 1.

Table 1. The track curves tested and corresponding to them super elevations

<table>
<thead>
<tr>
<th>Curve radius $R$ [m]</th>
<th>Superelevation $h$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>0.110</td>
</tr>
<tr>
<td>6000</td>
<td>0.051</td>
</tr>
</tbody>
</table>

On the inner rail of the track, there is a vertical irregularity described by half a sine wave with a wavelength corresponding to the number of adjacent sleepers that have lost support. Assuming that typical distance between sleepers is 0.65 m [1,10], the irregularity wavelengths corresponding to one, two or three adjacent sleepers that lost support were examined. The values are summarized in table 2. In each case, the deflection amplitude is constant at 0.01 m.

Table 2. The wavelengths of vertical track irregularity tested

<table>
<thead>
<tr>
<th>Number of adjacent sleepers without one side support</th>
<th>The irregularity wavelength $L$ [m]</th>
<th>The irregularity wavelength $L$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>5.2</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Changes of the wheel-rail contact forces of the first bogie leading wheelset on the inside of the arc, i.e. the wheel passing through the given track irregularity, were observed. Examples of changes in the value of vertical force $Q$ and lateral force $Y$ at a velocity of 20 m/s along a curved track with a radius of $R = 3000$ m through an irregularity with a wavelength of $L = 3.9$ m are shown in figure 2.

A characteristic feature of the VI-Rail tool is the ability to start calculations only on a straight track. Therefore, the simulation presented in figure 2 begins on a straight track, then passes the transition curve, and then the regular arc motion starts with a constant radius value. The irregularity negotiation causes a disturbance of the set values of contact forces on the curve track section. The minimum and maximum values generated by the irregularity passing are recorded for each motion simulation. The $Q_{stat}$ force results from the vertical pressure of the wheel on the rail in straight and smooth track conditions. Negative values of the lateral force $Y$ result from the adopted orientation of the coordinate systems applied in the tested vehicle-track model.
Fig. 2. The first wheelset inside wheel-rail contact forces. Curve track motion of curve radius $R = 3000$ m. Vertical force (a) and lateral force (b) during the vertical irregularity negotiation with velocity 20 m/s. Irregularity wavelength $L = 3.9$ m, amplitude $A = 0.01$ m (source: own elaboration)

Motion simulations of the form shown in figure 2 were conducted in the velocity range from 5 to 60 m/s. The upper value of this range is determined by the critical velocity $v_n$, which for this model is 61.7 m/s [3, 4, 5]. The values of contact forces obtained from these simulations were a source of information to present the impact of the irregularity wavelength on the contact force values in a wide range of velocity changes. It is also possible to compare the calculated values of contact forces to applicable standards and regulations in the field of rail vehicles' impact on the track [8, 9, 11, 12].

3. The model tested

The model was created with the use of VI-Rail engineering software. It is a discreet model of a 127A passenger car (fig. 3). Models of bogies correspond to the 25AN type bogie structure. The complete wagon model consists of 15 rigid bodies: a car body, two bogie frames, four wheelsets and eight axle boxes. Elastic and damping elements connect rigid bodies with
linear and bi-linear characteristics [6]. The wagon model is supplemented with a vertically and laterally flexible track model with parameters corresponding to the parameters of the European ballast track. Nominal profiles of S1002 wheels and UIC60 rails with an inclination of 1:40 were used. Nonlinear contact parameters are calculated using the ArgeCare RSGEO program. For calculations of wheel-rail tangential contact forces, the simplified Kalker's theory implemented in the form of the FASTSIM procedure is used [7]. Equations of motion are solved using the Gear procedure. The model is described in more detail in [3, 4, 5, 13].

![Diagram of vehicle-track model](source: own elaboration)

Fig. 3. The tested vehicle-track model diagram: a) side view, b) front view, c) top view

4. The results

Changes in the values of wheel-rail contact forces were observed: longitudinal $X$, lateral $Y$ and vertical $Q$. This is the internal rail course of the curve at which the given vertical irregularity occurs. Driving through the irregularity is the only reason for the change in contact force values on curve. The minimum and maximum values were read from the graphs with an example form shown in figure 2. These values, as a function of vehicle velocity, are shown in the following diagrams.
When passing through the irregularity, the minimum and maximum values of longitudinal forces do not change significantly (fig. 4). In the range of tested vehicle velocity of 5...60 m/s, the minimum values reach approx. -18 kN (for \( L = 3.9 \) m, figure 4b), while the maximum values approx. 26 kN (for \( L = 2.6 \) m, fig 4a). On a curve with radius \( R = 6000 \) m, the minimum values are smaller than the minimum values on a curve with radius \( R = 3000 \) m. But maximum values are slightly larger on a curve with a smaller radius.

The most extensive changes in lateral contact forces \( Y \) occur when passing through an irregularity with the shortest wavelength \( L = 2.6 \) m (fig. 5a). The minimum values then reach approx. -42 kN. For the wavelength of irregularity \( L = 3.9 \) m, the minimum values of lateral forces reach -20 kN and for \( L = 5.2 \) m reach approx. -17 kN. The maximum values of lateral forces for all wavelengths of irregularity reach a maximum of about 18 kN and for individual velocities are slightly higher on a curve with a larger radius.
The greatest impact of the set vertical track irregularity is evident in the values of vertical contact forces $Q$ (fig. 6). Both the velocity of vehicle motion and the wavelength of the irregularity have a significant impact on the values of vertical forces. The maximum $Q_{\text{max}}$ values increase as the velocity of motion increases. They reach the highest values for the shortest wavelength $L = 2.6$ m and exceed 250 kN on a curve with a smaller radius. For larger wavelengths of the irregularity, vertical forces are smaller and reach approx. 150 kN for $L = 3.9$ m and approx. 110 kN for $L = 5.2$ m. The largest effect of the curve radius on $Q_{\text{max}}$ is noticeable when passing through the irregularity with the wavelength $L = 2.6$ m at a velocity of 55 .. 60 m/s (fig. 6a). In other cases, the $Q_{\text{max}}$ values on both routes are similar.

The minimum values of vertical forces $Q_{\text{min}}$ decrease as the velocity of motion increases. Depending on the irregularity wavelength $L$ and the curve radius $R$, there is a characteristic value of the vehicle velocity, at which the minimum value of the vertical force $Q_{\text{min}}$ reaches zero. These values are listed in table 3.

<table>
<thead>
<tr>
<th>The irregularity wavelength $L$ [m]</th>
<th>Curve radius $R = 3000$ m</th>
<th>Curve radius $R = 6000$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L = 2.6$</td>
<td>17.7</td>
<td>22.1</td>
</tr>
<tr>
<td>$L = 3.9$</td>
<td>30.2</td>
<td>24.4</td>
</tr>
<tr>
<td>$L = 5.2$</td>
<td>35.5</td>
<td>43.6</td>
</tr>
</tbody>
</table>

In the real system, the value of $Q_{\text{min}} = 0$ can mean a momentary loss of wheel-rail contact and the emergence of conditions favourable to vehicle derailment. As can be seen in table 3 on both curves, the velocity at which $Q_{\text{min}} = 0$ increases as the irregularity wavelength increases. However, the influence of the curve radius is ambiguous. The value of the vertical force $Q_{\text{stat}}$ means the static value of this force (for zero-velocity of motion).

Diagrams presented in figure 7 and 8 allow comparing the calculated values of contact forces with the permissible values of forces in rail vehicle-track interaction. In the case of
lateral forces (fig. 7), the maximum values from the absolute values of lateral forces calculated for crossing over the irregularity of individual wavelengths \( L \) are presented in the diagrams.

Fig. 7. The maximum of internal wheel-rail lateral contact forces absolute values \( |Y|_{\text{max}} \) as a result of the vertical track irregularity negotiation with the irregularity wavelength: \( L = 2.6 \) m, \( L = 3.9 \) m and \( L = 5.2 \) m on curves of radius \( R \): a) 3000 m and b) 6000 m.

(source: own elaboration)

The Prudhome criterion in the form given in [10,11] was adopted to compare the calculated and permissible values of lateral forces (1). It makes the sum of acceptable lateral forces acting on a two-meter long track section, dependent on the type and condition of the track and the vertical axle load (pressure of the wheelset on the track) (1). Assuming the value of \( K = 0.85 \) recommended for average operating conditions of ballast track and \( 2Q = 111 \) kN for the modelled wagon in a loaded state, the permissible value of the sum of lateral forces was estimated at \( \Sigma Y_{(2m)} = 39950 \) N.

\[
\lim \Sigma Y_{(2m)} \leq K \left( 10 + \frac{2Q}{3} \right) \quad [kN]
\]

where:

- \( K \) – the coefficient dependent on sleepers type, ballast and ballast compaction,
- \( 2Q \) – the static axle pressure on track in [kN].

As can be seen, only when passing through the irregularity with the shortest wavelength \( L = 2.6 \) m, the lateral forces exceed the allowable value on both curves tested at a velocity above 56...58 m/s. However, for longer irregularity wavelengths, the lateral forces do not exceed 20 kN in the entire velocity range.

The maximum values of the vertical vehicle-track forces are summarized in figure 8. The permissible values of wheel-rail vertical contact forces \( Q \) are specified in the standard [8]. It determines specific \( Q \) values depending on the allowable velocity of vehicle motion on the analysed track section. Extreme values are 160 kN on sections with a permissible velocity of \( v \geq 300 \) km/h and 200 kN for \( v \leq 160 \) km/h. Both values are marked in figure 8.
As can be seen, passing through an irregularity with the shortest wavelength causes the criterion values to be exceeded on both tested curves at a motion velocity above 42…44 m/s. For longer irregularity wavelength, the vertical forces also increase according to vehicle velocity increase, but in the tested velocity range, they do not exceed the criterion values.

![Fig. 8](image.png)

**Fig. 8.** The maximum of internal wheel-rail vertical contact forces values $Q_{\text{max}}$ as a result of the vertical track irregularity negotiation with the irregularity wavelength: $L = 2.6$ m, $L = 3.9$ m and $L = 5.2$ m on curves of radius $R$: a) 3000 m and b) 6000 m (source: own elaboration)

### 5. Conclusion

Simulation tests were performed to assess the impact of the chosen form of track damage on the wheel-rail contact forces concerning the current vehicle-track interaction criteria. Test results show a significant effect of irregularity wavelength on the value of contact forces. The highest values of vertical and lateral forces occurred during the passage through the irregularity of the shortest from among the tested wavelengths $L = 2.6$ m. Crossing through such irregularity at a velocity greater than 42 m/s may lead to exceeding the permissible values of the vehicle's impact on the track specified in regulations. At larger irregularity wavelengths, the wheel-rail contact forces also increased with increasing velocity but did not exceed the permissible values in the tested velocity range. However, one should remember about the adopted assumption of a constant value of deflection amplitude $A = 0.01$ m for all irregularity wavelengths. With a defined vehicle mass and longer irregularity (several adjacent sleepers not supported), greater deflection amplitude should be expected.

The test results show the importance of proper track maintenance for vehicle safety of motion. Temporary vertical force values $Q = 0$ may indicate a loss of wheel-rail contact. The widely used safety factor against derailment $Y/Q$ reaches then very high values (theoretically $\infty$). Conditions favourable to derailment are initiated then. Exceeding the permissible value of the vehicle-track lateral forces means the existence of conditions favouring permanent lateral displacement of the rails with sleepers relative to the ballast. The modelled wagon bogies wheelbase is $2a = 2.5$ m (fig. 1b and 3). Driving through the irregularities...
of the studied wavelength $L$, occurring on one rail track only is the so-called track twist. Very unfavourable loading (stress) conditions of the bogie frame and other elements of the bogies then appear.

References