Assessment of Dynamics of a Rail Vehicle in Terms of Running Properties While Moving on a Real Track Model

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Abstract: Simulation computations represent a very effective tool for investigating operational characteristics and behaviours of vehicles without having a real product. The rail vehicles sector is typical, in that simulation computations including multibody modelling of individual vehicles (i.e., wagons) as well as entire trainsets are widely used. In the case of designing rail vehicles, running safety and ride comfort are two of the most important assessment areas. The presented work is focused on the research of the dynamical effects of a rail vehicle while running on a railway track created in a commercial multibody model. There is a lot of research focused on the investigation of dynamic performances while a rail vehicle is running on a flexible railway track. The real operation of a rail vehicle meets problems on track, where the stiffness-damping parameters of a railway track vary in transient sections (e.g., the exit of a tunnel). This work brings a contribution to research related to the assessment of the dynamic response of a rail vehicle on a chosen track section. A passenger railway vehicle is chosen as a reference multibody model. Simulation computations were performed for three different railway track models, i.e., for a rigid track model and for a flexible track model defined in two different manners. The stiffness-damping parameters of the rail vehicle are defined symmetrically in relation to the longitudinal axis of the vehicle, e.g., they are the same values for the left and right side. The centre of gravity is not located symmetrically, but it is partially shifted in the lateral direction. This can be observed in the results of wheel forces and their waveforms. There are evaluated values and waveforms of the vertical wheel forces, the lateral wheel forces and the derailment quotient. The obtained results have revealed the influence of the railway track formulation in the model on the output parameters.

Keywords: rail vehicle; simulation computations; multibody model; derailment quotient; running safety; rail track model

1. Introduction

Dynamical analyses of rail vehicles serve for the investigation of its running properties in terms of its movement on a track together with the causes of their changes. It is possible to investigate a vehicle as a unit or as only its individual subsystems (e.g., wheelset, bogie, etc.), and these are mainly evaluated on acting forces, velocities and accelerations, as well as other quantities. They use various ways and methods of analysing and evaluating dynamical effects and running properties [1–3].

Simulation calculations are focused mainly on the investigation of the dynamics of a rail vehicle mechanical system. It is most often excited by track irregularities [4–6]. Other phenomena are also important, such as quasistatic equilibrium states evaluated during running in curves, further eigenfrequencies and related eigenmodes, transfer functions, etc. [7–10].

The creation of a representative model of a rail vehicle is the first and necessary step for performing an analysis of the running properties of a rail vehicle by means of
simulation computations. It requires one to parse in detail the mechanical system of a rail vehicle to find the essential data about the vehicle, which are its geometrical parameters, masses and moments of inertia of individual components, further characteristics of elastic couples, external loads, and others. It leads to the setting-up of a dynamic model of a rail vehicle. Based on the dynamic model, a mathematical model is derived. In the case of the creation of a rail vehicle dynamical model using commercial software, the mathematical model is set up automatically. In terms of the mathematics, it is composed of differential-algebraic equations. In terms of the mechanics, these equations are called equations of motion [11–15].

The main goal of this research is to investigate the dynamical properties of a rail vehicle by means of simulation computations. The main quantities needed are the vertical wheel forces marked $Q$, the lateral wheel forces marked $Y$ and their ratio $Y/Q$, which expresses the important quantity, i.e., the derailment quotient. These quantities are essential for the evaluation of running safety and the railway track load level [16–20].

2. Research Motivation

The authors of the presented work perform an investigation of vehicle properties in terms of their dynamical responses and effect over a long time. They have developed a number of various models of vehicles with a focus on rail vehicles and road vehicles [21–25]. These activities have led to the number of results, which are mainly aimed at the evaluation of two areas, namely the ride comfort for passengers [23,25] and the operational safety [22,24]. These areas have been assessed for various parameters of vehicles and for various types of rail and road vehicles. During these modelling activities, interesting findings were revealed, which relate with the various approaches to a simulation model of a rail vehicle, mainly in terms of its complexity [21,22,26].

This research concludes selected findings about the effects of changes in the stiffness-damping parameters of a suspension system of a passenger rail vehicle as well as the effects of various formulations of a railway track model to the dynamical forces in the wheel/rail contact. The values of derailment quotient are evaluated based on the standards [27,28]. These works are conducted by many researchers to investigate rail vehicle dynamics as a key factor affecting their operational safety. It relates to the increasing running speed of railway vehicles and with the intent to ensure reliable and safe operation on railway lines as much as possible [29–32].

3. A Mathematical Approach to the Problem

The investigation of rail vehicle dynamics is performed by simulation computations and by experimental tests. Real experiments are financially demanding and time consuming, but they allow us to reveal the actual behaviour of a dynamic system of a rail vehicle on a particular railway track. Simulation computations reduce the needed costs as well as time for performing analyses. However, their adequacies are limited to the available input data about the mechanical system of a rail vehicle and a railway track. The next part of this work is aimed at simulation computations. Section 3 contains a general mathematical description of a solved mechanical system.

3.1. A Rail Vehicle Model

A virtual model represents a rail vehicle by a system of bodies, which are interconnected by flexible massless elements. As was mentioned above, the mathematical description of a virtual model of a rail vehicle is composed of a system of equations of motion, and it is generated automatically by simulation software. For the presented research, a Simpack software package (Dassault Systèmes, Vélizy-Villacoublay, France) has been used. It is a robust simulation tool for the creation, simulation and analysis of various mechanical systems including a mechanical system of transport means. In particular, the Simpack software is a powerful software package in the field of railway technologies [21,22,33–36]. It has implemented the most known algorithms for the calculation of a specific phenomenon.
related with wheel/rail contact, which plays a very important and key role in rail vehicle dynamics [37,38] and whose proper setting is also essential for correct calculations of wanted output quantities in this presented work.

In terms of the mechanics, a considered rail vehicle consists of several rigid bodies connected by force elements (coil springs and hydraulic dampers). Force elements are supposed to be massless. Moreover, between individual bodies are restricted, required degrees of freedom of mechanical joints and kinematic couplings. Between wheels and rails are defined special coupling elements for the calculation of forces and other quantities in the wheel/rail contact [39,40]. In our case, the FASTSIM wheel/rail model is defined [41–43]. All force elements, joints, couplings, wheel/rail contact elements and their characteristics are defined symmetrically in relation to the longitudinal symmetry plane. A dynamic scheme of a solved rail vehicle in a side view is shown in Figure 1.

The resulting system of equations of motion consists of non-homogenous differential equations [11,44], which are usually nonlinear and can be written as follows:

\[
M \ddot{q}(t) + (B + \Omega_0 \cdot G) \dot{q}(t) + (K + \Omega_0^2 \cdot Z) \cdot q(t) = h(t)
\]  

(1)

where \( q(t), \dot{q}(t) \) and \( \ddot{q}(t) \) are the vector of generalized coordinates, velocities and accelerations, respectively, \( M \) is the mass matrix, \( B \) is the damping matrix and \( K \) is the stiffness matrix. Matrices \( \Omega_0 \cdot G \) and \( \Omega_0^2 \cdot Z \) describe the gyroscopic and inertia forces.

Figure 1 shows a simplified dynamical scheme of the investigated rail vehicle with the main components marked as follows: \( M_B \) is the wagon body mass, \( M_B \) is the mass of bogies, \( M_w \) is the mass of wheelsets, \( J_B \) is the wagon body moment of inertia, \( J_B \) is the moment of inertia of bogies, \( J_w \) is the moment of inertia of wheelsets, further, \( k \) indicates stiffness of coil springs and \( b \) means the damping coefficient of the hydraulic dampers. The masses of rigid bodies are concentrated in their centres of gravity, which are marked by \( C_B \) for the wagon body, \( C_b \) for bogies and \( C_w \) for wheelsets. The rest of the quantities indicate generalized coordinates and are marked as follows: for vertical direction of a wagon body (\( z_B \)), bogies (\( z_b \)) and wheelsets (\( z_w \)), for longitudinal direction of bogies (\( x_b \)), for lateral direction of a wagon body (\( y_B \)), bogies (\( y_b \)) and wheelsets (\( y_w \)); further, generalized coordinates are included for angular deflection around the longitudinal axes for the wagon body (\( \psi_B \)), bogies (\( \psi_b \)) and wheelsets (\( \psi_w \)), around the lateral axis for the wagon body (\( \phi_B \)) and for bogies (\( \phi_b \)), and finally around the vertical axis for the wagon body (\( \zeta_B \)), bogies (\( \zeta_b \)) and wheelsets (\( \zeta_w \)). Generally, the right side of equations of motion describes the external load of a mechanical system, i.e., the excitation of the system [6,7,45]. In the case of the rail vehicle, this would be the load from the rail profile and track irregularities.
vehicle, the excitation is most often caused by track irregularities [46–49]. Hence, the vector \( h(t) \) is the vector of kinematic excitation of the rail vehicle containing parameters of railway track irregularities [50,51]. Due to the symmetry of a rail vehicle, equations of motion can be divided into two separate systems for symmetrical and asymmetrical motions.

### 3.2. A Railway Track Model

A railway track model for simulation computations needs to have its geometry, flexibility [52,53] as well as its irregularities defined [54,55].

Nominal railway track geometry is defined by its ideal position, which is given by straight track section, curves radii, lengths of individual curves, sections in superelevation ramps and transition sections, rail cants, and others [36,56,57].

A railway track model is supposed to be the definition of rail head profiles and a prescription of input values regarding running on a track, further layout and arrangement of track irregularities and wheel/rail profile wear [1,58]. Ideal track geometry is defined separately from parameters defining real inputs for deviations from the ideal position together with track irregularities.

If a multibody model includes a flexible track model, a track model consists of one rigid body, two rigid bodies or several rigid bodies. Then, these bodies substitute masses of rails and are connected by flexible couplings.

In the Simpack programme package, the railway track is created either directly in the user’s interface or by means of a configuration file. Both contain required parameters as follows:

- A horizontal profile;
- A vertical profile;
- Rail head profiles;
- Track irregularities.

Track irregularities result in kinematic excitations of the rail vehicle mechanical system when it moves on a railway track, and they influence its dynamic response. Usually, track irregularities are described for lateral and vertical direction separately. In the Simpack software, it is possible to prescribe track irregularities by a harmonic function, by the power spectral density or by the input data, which are obtained from real measurements.

Track irregularities described by a harmonic function are the simplest way. The PSD description simulates track irregularities, which are closer to the reality. The measured track irregularities simulate the most realistic effect to a rail vehicle. Some parameters of track irregularities needed for the input file are shown in Figure 2, where \( y \) is the deviation in lateral direction, \( z \) is the deviation in the vertical direction, \( \phi \) is the angle deviation and \( s_0 \) is the nominal track gauge [59]. Lower indices \( L \) and \( R \) for deviations (Figure 2) mean left and right rails, respectively. A model of the railway track used in this research includes its flexibility. A more detailed description of the railway track model used in the solved task is introduced in Section 5.2.

![Figure 2. Parameters of railway track irregularities [59].](image-url)
4. A Multibody Model of an Investigated Rail Vehicle and a Railway Track

The following section introduces an applied method for the creation of an MBS model of a rail vehicle and a railway track. Both have been within one assembly, and this has been set up by several substructures described below.

4.1. A Description of a Wagon Model

Simulation computations have been performed with a rail vehicle model representing a railway passenger wagon. This wagon model in the Simpack software package comprises three substructures, namely for the body of the wagon, a front bogie and a rear bogie (in the running direction). The wagon is equipped with a two-level suspension system, the first level between the wheelsets and a bogie frame and the second between a bogie frame and the body of the wagon. Both suspension systems consist of coil springs and hydraulic dampers.

From the mechanics’ point of view, the computational wagon model is created by rigid bodies with defined mass and inertia parameters, and these bodies are interconnected by massless flexible components, which are called force elements in the Simpack. A view of the created multibody model of the passenger wagon is shown in Figure 3.

![Figure 3. A view of the multibody model of the investigated passenger wagon created in the Simpack software package.](image)

The wagon bogie is shown in Figure 4. It contains a designation of individual components of suspension systems, which are important in relation to other research procedures described below (Section 5). Thus, these components are denoted as follows:

- $k_p$ is the stiffness of the primary spring;
- $k_s$ is the stiffness of the secondary spring;
- $b_{PV}$ is the damping coefficient of the primary vertical damper;
- $b_{PY}$ is the damping coefficient of the primary yaw damper;
- $b_{PL}$ is the damping coefficient of the primary lateral damper;
- $b_{SV}$ is the damping coefficient of the secondary vertical damper.

![Figure 4. The wagon bogie with denoted of individual components of suspension systems.](image)
4.2. A Description of a Railway Track Model

The railway track is another important part of the entire multibody model. In our research, we have chosen a railway track model of a real railway track section. The used track model is suitable for performing the simulation computations needed and subsequent evaluation of dynamical quantities, because it includes not only straight sections, but also sections with curves of various radii, superelevation ramps, transient sections, etc. The track gauge is 1435 mm, the rail head profile is UIC60 and the rail cant is 1:40. There parameters are defined in the track input file. A view of the track in the horizontal plane of the railway track model is shown in Figure 5.

Figure 5. An illustration of the created railway track.

The modelled railway track has defined the kind of superelevation for all curves about the inner side. It means that the inner side of the track remains at the same level, and the outer side is raised by the full superelevation. The track centreline is raised by the half superelevation.

The definition of the railway track model has also incorporated track irregularities. The definition of irregularities in the track model is important in terms of excitation of the passenger car to simulate as real conditions as possible. The model of the railway track used included measured track irregularities in the vertical and horizontal directions of both rails. Track irregularities have been defined by means of an input file, where individual deviations from an ideal geometry are prescribed. The track irregularities have been defined with the step of 0.5 m. An illustration of track irregularities used in the track model is in Figure 6. This track model has led to the generation of rail vehicle excitations and to related observable dynamical effects [60–62].
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Figure 6. An illustration of the parts of the track irregularities prescribed in the track model: (a) a left rail, a lateral direction; (b) a right rail, a lateral direction; (c) a left rail, a vertical direction; (d) a right rail, a vertical direction.

5. Results of Simulation Computations

The main goal of this investigation’s activities is to investigate how the change of suspension parameters of the passenger car affects the dynamic forces and how the track flexibility affects them.

5.1. Influence of Suspension Parameters Changes

Parameters of the coil spring and hydraulic damper of the first level and second level suspension are changed in three manners. There are components of suspension system denoted in Figure 4 (stiffness $k_P$ and $k_S$ and damping coefficients $b_{VD}$ and $b_{VD}$). In doing so, the ratio of the stiffness of secondary and primary springs as well as the ratio of the damping of the vertical secondary and the vertical primary dampers have been preserved. Damping coefficients of the rest of the dampers were unchanged. The stiffness characteristics of the springs are linear, and the characteristics of the damping coefficients are non-linear.

The definition of spring-damping parameters that come from the original parameters is named “Original”. The ratio of stiffness $k_S/k_P$ is 0.587. In the case of damping coefficients, an inclination of the tangent has been changed and the ratio of the extreme values has been preserved. Then, many combinations of the $k_P$ and $k_S$, and characteristics of $b_{PV}$ and $b_{SV}$ are defined and tested by means of simulation computations. This work presents only the finally chosen combinations of the $k_P$ and $k_S$, and $b_{PV}$ and $b_{SV}$ for illustration of their effects on the dynamical response of the rail vehicle. These parameters are listed in Table 1. The percentage of $k_P$, $k_S$, $b_{PV}$ and $b_{SV}$ expresses what percentage the original value has changed. It has been changed both to a lower (sign “−”) and higher (sign “+”) value.
Simulation computation of the rail vehicle is performed for various running speeds. This section brings waveforms of the derailment quotient for the running speed of 60 km/h. This speed represents an average speed for the chosen track sections, and it sufficiently illustrates the observed results.

Figures 7–9 show waveforms of the output value, i.e., derailment quotient, which is expressed as the \( Y/Q \) ratio. As it was mentioned above, it is the key factor for the evaluation of running safety of rail vehicle running in curves. There are displayed results for the original vehicle, modification I and modification II.

### Table 1. List of parameters of the spring-damper elements.

| Designation | Name       | Stiffness | Damping |
|-------------|------------|-----------|---------|
| O           | Original   | 0%        | 0%      | 0%      | 0%      |
| I           | Modification I | -45%    | +45%    | -45%    | +45%    |
| II          | Modification II | +45%    | -45%    | +45%    | -45%    |

Figure 7. The derailment quotient \( Y/Q \) for “Original” parameters, a real track with irregularities, a running speed of 60 km/h.

Figure 8. The derailment quotient \( Y/Q \) for “Modification I” parameters, a real track with irregularities, a running speed of 60 km/h.
where $k$ is the frequency, $L$ is the travelled distance, $L_0$ is the offset of the initial input in the track model for smooth convergence of an iteration step, $b$ is the damping coefficient, $\omega$ is the amplitude of $L$, and $\theta$ is the angle of rotation.

The derailment quotient $Y/Q$ for “Modification II” parameters, a real track with irregularities, a running speed of 60 km/h.

The values of the $Y/Q$ ratio in neither case have exceeded the limit value, which is for curves of the track model of $Y/Q_{lim} = 0.8\ [27,28]$. The analysed vehicle ran through curves in all tested cases safely.

As it can be seen, the original suspension system does not ensure the damping of the vehicle after running through curves (Figure 7, the time ranges are 60 s to 70 s and 210 s to 350 s), and amplitudes of the derailment quotient are higher in comparison with results for modification I and modification II.

5.2. Influence of Railway Track Flexibility

Simulations of a rail vehicle in simulation software are usually performed for a rigid railway track. However, there are technical applications, for which it is necessary to consider the fact that a railway track and its subsoil are not ideally rigid, but they have a certain flexibility. Such a multibody model of a rail vehicle and a railway track is supplemented by other bodies, kinematic and mechanical joints with defined degrees of freedom, stiffness-damping parameters in individual directions and others.

The Simpack program package allows us to set up such a model of a flexible railway track, which can be more or less difficult. The formulation of the flexible track is performed in this particular software during the modelling of a bogie, namely during defining wheel/track contact parameters. Then, it is loaded to the entire model of a rail vehicle.

In principle, the stiffness-damping parameters, i.e., stiffness and damping coefficients in joints between individual bodies representing sleepers, can be defined in two manners:

- By defining constant values of stiffness-damping parameters;
- By defining a functional dependency of stiffness-damping parameters; parameters depend on a travelled distance and such an approach takes into account changes of stiffness-damping parameters under sleepers and between sleepers.

A scheme of a flexible railway track model used in the research is shown in Figure 10.

In the presented work, both approaches of modelling a flexible railway track have been applied. Formulations used for modelling stiffness-damping parameters are as follows:

\[
k_i(L) = k_{i0} + k_{iC} \cdot \sin[\omega_L \cdot (L(t) - L_0)], \quad i = y, z, \phi,
\]

\[
b_i(L) = b_{i0} + b_{iC} \cdot \sin[\omega_L \cdot (L(t) - L_0)], \quad i = y, z, \phi,
\]

where $k_i(L)$ is the stiffness of the track in individual directions $k_i(L)$ (depending on the travelled distance), $k_{i0}$ is the constant stiffness in individual directions, $k_{iC}$ is the stiffness amplitude, $\omega_L$ is the frequency, $L(t)$ is the travelled distance, $L_0$ is the offset of the initial input in the track model for smooth convergence of an iteration step, $b_i(L)$ is the damping coefficients in individual directions and others.
coefficient in individual directions, \( b_{i0} \) is the constant value of the damping coefficient in individual directions and \( b_{iC} \) is the amplitude of the damping coefficient. The values of stiffness and damping coefficients are defined in the model symmetrically in relation to the longitudinal plane of symmetry, i.e., the same parameters are defined for both right and left sides of the track. Parameters of the elastic track foundation have been defined according to \[63\]. The stiffness-damping parameters of the flexible track are constant independently of whether it is the straight section or the sections with curves.

![A scheme of a flexible railway track model used in the research](image)

**Figure 10.** A scheme of a flexible railway track model used in the solved task.

To identify the obtained results for various formulations of the railway track models, the following designations are used:
- A rigid track is denoted as “Rigid”;
- A flexible track with constant stiffness-damping parameters is denoted as “Flex\_const”;
- A flexible track with variable stiffness-damping parameters is denoted as “Flex\_sin”.

Constant values of stiffness-damping parameters for a flexible track model are listed in Table 2.

**Table 2.** Parameters of the flexible railway track model \[63\].

| Parameter                           | Designation | Value          |
|-------------------------------------|-------------|----------------|
| Stiffness in the vertical direction | \( k_z \)   | \( 1.49 \times 10^8 \) N/m |
| Damping in the vertical direction   | \( b_z \)   | \( 2.10 \times 10^5 \) Ns/m |
| Stiffness in the lateral direction  | \( k_y \)   | \( 4.21 \times 10^7 \) N/m |
| Damping in the lateral direction    | \( b_y \)   | \( 10.12 \times 10^4 \) Ns/m |
| Torsion stiffness (around \( x \) axis) | \( k_\phi \) | \( 8.77 \times 10^7 \) Nm/rad |
| Torsion damping (around \( x \) axis) | \( b_\phi \) | \( 1.25 \times 10^5 \) Nms/rad |

Parameters of the tested rail vehicle correspond with values for the “Original” vehicle described in Section 5.1.

For assessment of the rail vehicle in terms of running safety and track loading, vertical wheel forces, lateral wheel forces and the described derailment safety are important.

Resulting waveforms of vertical wheel forces, lateral wheel forces and derailment quotient for the set running conditions are shown in Figures 11–13. Results are for the running speed of 60 km/h and for the “Rigid”, “Flex\_const” and “Flex\_sin” track formulations.
Torsion damping (around $x$ axis) $b\phi = 1.25 \times 10^5$ Nms/rad

Parameters of the tested rail vehicle correspond with values for the "Original" vehicle described in Section 5.1. For assessment of the rail vehicle in terms of running safety and track loading, vertical wheel forces, lateral wheel forces and the described derailment safety are important.

Resulting waveforms of vertical wheel forces, lateral wheel forces and derailment quotient for the set running conditions are shown in Figures 11–13. Results are for the running speed of 60 km/h and for the "Rigid", "Flex_const" and "Flex_sin" track formulations.

**Figure 11.** Waveforms of the vertical wheel forces ($Q$), lateral wheel forces ($Y$) and derailment quotient ($Y/Q$) for the “Rigid” track.

**Figure 12.** Waveforms of the vertical wheel forces ($Q$), lateral wheel forces ($Y$) and derailment quotient ($Y/Q$) for the “Flex_const” track.
When the observed wheel force waveforms are evaluated for different track formulations, it can be seen that the use of the flexible track model with constant values of stiffness-damping characteristics (“Flex_const”) leads to partial damping of dynamical effects of the running rail vehicle. Amplitudes of vertical wheel forces \( Q \) are lower mainly while running in curves. The higher damping effect is also registered for lateral wheel forces \( Y \) as well as for the derailment quotient \( Y/Q \). The derailment quotient is higher for running in curves in comparison with running in straight track sections.

Achieved results of simulation computations have shown that amplitudes of the vertical wheel forces \( Q \), the lateral wheel forces \( Y \) and thus also the values of resulting derailment quotient \( Y/Q \) are significantly higher for the flexible formulation (“Flex_sin”) of a railway track in comparison with the results for the “Rigid” track formulation and for the “Flex_const” track formulation. It is possible to conclude that these higher amplitudes are caused by the variable parameters along the track. The model used does not describe the real situation of the actual railway track. This phenomenon can be improved by an implementation of values obtained directly from experimental measurements on a particular track section. Such parameters could replace the input data in the current model of the railway track.

The presented work shows the possibilities of creating an adequate model of a rail vehicle and a railway track with track flexibility. The objective of the authors’ work is based on a close collaboration with researchers from the university to obtain parameters of railway tracks from real railway track sections as well as vehicle operated on these lines. These parameters will be real inputs for simulation models, which will serve for the calculation of certain problematic track sections. Potential adequate results from simulation computations will be useful for building or reconstructing railway tracks, and the unwanted behaviour of railway track substructure after a train passes will be detected before expensive construction interventions [64,65].

**Figure 13.** Waveforms of the vertical wheel forces \( Q \), lateral wheel forces \( Y \) and derailment quotient \( Y/Q \) for the “Flex_sin” track.
6. Conclusions

Computer simulations are widely used for the investigation and assessment of dynamic effects of rail vehicles while running on a railway track.

Analysis of running safety is still a current problem and a distribution of forces in wheel/rail contact is very important. Here, we investigated mainly vertical wheel forces in terms of the track loads and lateral forces, which determine running safety during movement in curves. Then, the ratio of vertical wheel forces and lateral wheel forces gives the derailment quotient, and the limit values are included in the specific standards.

In the presented research:

- The commercial simulation software Simpack has been used for the creation of a multibody model of a rail vehicle;
- A virtual model of a passenger car as well as a railway track model with track flexibility has been set up;
- The dynamic forces and the derailment ratio have been evaluated for three levels of stiffness-damping coefficients of the rail vehicle and for three various track flexibility formulations;
- It was concluded that the stiffness of springs and damping coefficients of dampers of the primary suspension leads to better damping of the rail vehicle mechanical system while running on a track. In the case of the flexible track formulation, the definition of stiffness-damping parameters of the track subsoil leads to higher amplitudes in comparison with the rigid track formulation.

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