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SPERLING'S COMFORT INDEX STUDY IN A PASSENGER CAR WITH INDEPENDENTLY ROTATING WHEELS

Summary. In this article, we compare the dynamic characteristics of cars with integral wheelsets and wheelsets with independently rotating wheels. We use Sperling's comfort index to assess the riding comfort. We compare the riding comfort of passenger cars with integral wheelsets and wheelsets with independently rotating wheels based on Sperling's comfort index.

1. INTRODUCTION

Examining the physical properties of train bogies, two types of bogies can be observed: bogies with solid wheels and bogies with independently rotating wheels. Although typical rolling stock bogies have been in use for a long time and most of their features are known, some aspects are further explored by the scientific community, such as stability indicators, vibrations, atypical bogie combinations in a train and operation of bogies in special climatic conditions. For railway bogies, bending characteristics and stability when driving at high speeds are important, but in general, they contradict each other. These reporting methods can provide consistency between bending performance and hunting stability. The following methods were adopted: optimized wheel tread profile, independently rotating wheels and asymmetric arrangement of longitudinal primary stiffness. New bogies have been successfully developed, which not only have excellent cornering characteristics but also good hunting stability [1].

The theory of elimination of longitudinal vibration in bogies as a dynamic vibration damper (DVA) for simple and easy reduction of vertical bending vibration of railway car bodies is proposed [2]. Under extremely low temperature operating conditions, a vehicle with a relatively small wheel equivalent conicity could be subjected to vehicle hunting, which impairs driving comfort. The proposed minimum wheel equivalent conicity is greater than 0.1. [3]. Applying the theory of nonlinear dynamical systems, the effect of wheel speed perturbations on wagon bogies was determined. [4].

The topic of rolling stock derailment and various related researches in the field of science are not new phenomena [5]. Scientists often study the influence of the wheel-running surface, its flange geometry and wheel dynamics on the derailment of a train [6]. In order to examine this issue in more detail, the phenomenon of flange climbing on the rail is usually examined [7]. The scientists concluded that this regularity is best described by the classical derailment equation [8], as it deals with wheel and rail friction slip. In addition, an approximate analytical formula describes the impact of wheel/rail creep forces [9]. Chinese researchers tested derailment due to wheel impacts on the rail as a type of dynamic derailment by estimating wheel jump height, later impact force and vertical wheel load. The factors analyzed were the speed of the wheelset, the side impact, the wheel flange angle, the wheel/rail friction coefficient and the vertical load on the wheel and the impact time interval during wheelset derailment [10]. It is very important to study low-radius track curves (180–300 m) in small-area countries or mountainous areas. There is a huge difference in the rolling radius of the wheelsets and it greatly determines the rolling laws [11]. Scientific papers also focus on the effect of vehicle wheel and rail friction modifiers on road curves and their influence on vehicle running as well as the condition of other chassis parts [12, 13]. Studies on the effect of wheel defects on rolling stock dynamics must be mentioned as a specific area of research [14]. However, as transport is focused on passenger service, one of the key issues should be studies on passenger comfort [15]. When examining the possibility of using independently rotating wheels, issues such as train running on the curve, active wheel steering systems, improved wheel profile and other theoretical or practical research are usually studied.

By actively wheelset steering, we can expect significant energy savings in the future. With an active wheel steering system, the wear of the wheel surface has its own regularities. Different wheel steering schemes are proposed in different patterns of wheel surface wear; these are discussed in this article. The developed steering system has good stability properties, as it adapts well to sharp track curves. The proposed steering system operates on the basis of independently rotating wheels, and it has low vibrations and good control on curves [16]. The study found that with wheels with reverse conicity (conicity toward the center of the track), a bogie (with independently rotating wheels) control scheme can be developed. Computer simulations and practical studies have shown that independently rotating wheels with inverted conicity have good dynamic performance [17]. The scientific literature presents the principles of operating various bogies with independently rotating wheels as well as the peculiarities of bogies and their production. [18].

It should be noted that the parameters and characteristics of a wheelset with independently rotating wheels are regulated by law. In research, they are also examined by scientists, for example, the standard ISO 2631, EN 12299 [19]. However, legal issues are not the focus of this article.

One of the more interesting aspects of researching train suspensions is the influence of their parameters on passenger comfort. One of the passenger comfort indicators is Sperling's comfort index. An objective of this study is to examine the dynamic characteristics of passenger cars with integral wheelsets and wheelsets with independently rotating wheels by using available scientific expertise and computer equipment, as well as test when Sperling's comfort index can be used to assess the riding comfort. Along with the comparison of the dynamics of cars with different wheelsets according to the comfort index, it will be interesting to compare the wear indicators in tangent and curved sections of the track; however, this is the subject of a separate study.

2. METHODOLOGY OF THE STUDY

Computer simulation with the "Universal Mechanism" (UM) software package was selected for the research for several reasons. Use of this software package allows performing many more studies in a relatively short time compared with studies using real rolling stock. The software allows analyzing vehicle dynamics depending on wheel and rail profiles, rolling stock suspension, chassis and railway parameters. The passenger car model consists of a body, two bogies and four pairs of wheelsets. The passenger car structure is modeled with two types of wheelsets: integral wheelsets (shown in Fig. 1) and wheelsets with independently rotating wheels.

The wheelset shown in Fig. 1 has six degrees of freedom that allow the entire wheelset to rotate and move in X, Y and Z axes. The wheelset with independently rotating wheels is shown in Fig. 2.

The wheelset shown in Fig. 2 is not integral and consists of 4 parts: axle, two wheels and bearing. The wheels of this wheelset can rotate independently; thus, the mechanism has seven degrees of freedom. The wheel profiles of both types of wheelsets used are the UIC510-2-type profiles. The bogie shown in Fig. 3 consists of two wheelsets, a frame, four axle boxes and a double-spring suspension.

The main technical details of the examined passenger car are presented in Table 1.

During the passenger car modeling, it is assumed that all bodies are rigid and can move in X, Y and Z axes. The bogie models of passenger cars in "Universal Mechanism" software with integral wheelsets and with independently rotating wheels are presented in Fig. 4a and Fig. 4b.

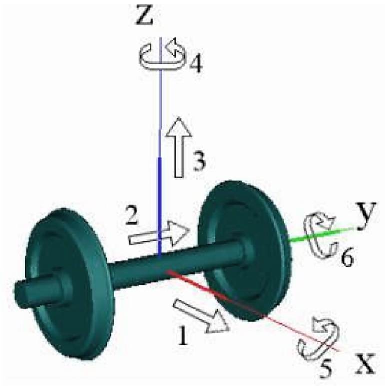

Fig. 1. Degrees of freedom of the integral wheelset

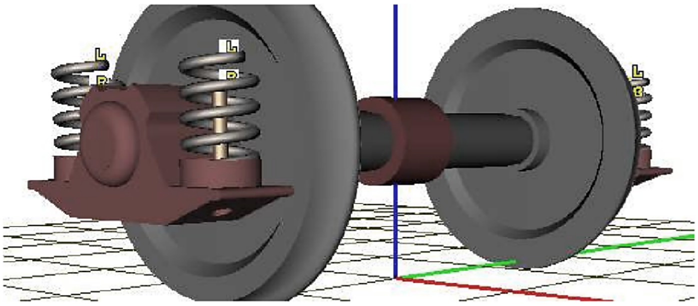

Fig. 2. Wheelset with independently rotating wheels

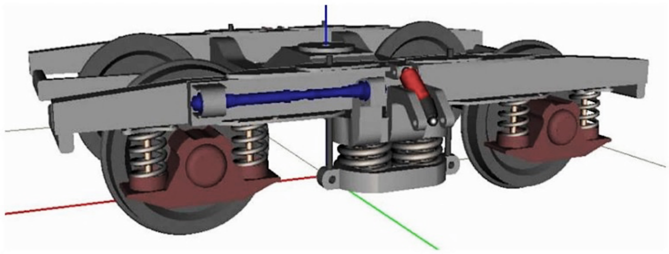

Fig. 3. Structure of a passenger car bogie

Table 1

Passenger car model parameters

Characteristics	Value
Car body mass, kg	54 700
Wheelset mass, kg	2000
Suspension type	Springs with hydraulic dampers
Wheelset base, mm	2 400
Bogie width, mm	2 218
Bogie length, mm	3 920
Wheel rolling radius, m	0.475
Half-sleeper width, m	1.2

The track irregularities shown in Fig. 5 were measured in a real UIC 60 railway, since they correspond to the real irregularities of the selected rail profile. 200 m and 2900 m radius track curves and a 1000 m length straight section were designed for this study. The curves are shown in Fig. 6.

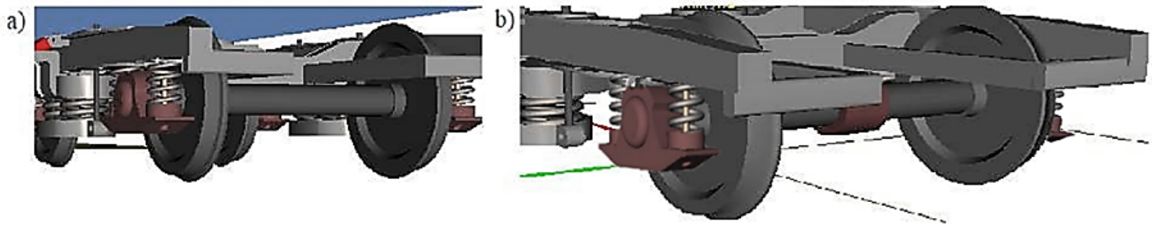

Fig. 4. Bogie model of passenger cars in "Universal Mechanism" software: a) with integral wheelsets and b) with independently rotating wheels

Horizontal and vertical irregularities in the 1000 m section of the modeled track are shown in Fig. 5.

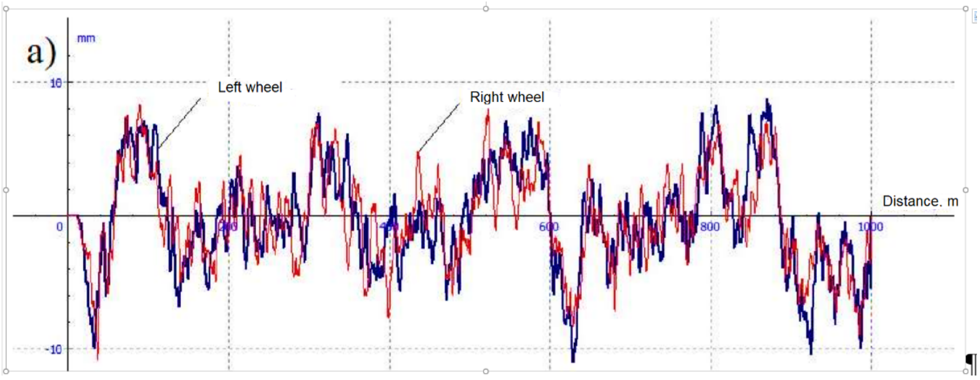

Fig. 5a. Vertical irregularities of the modeled track

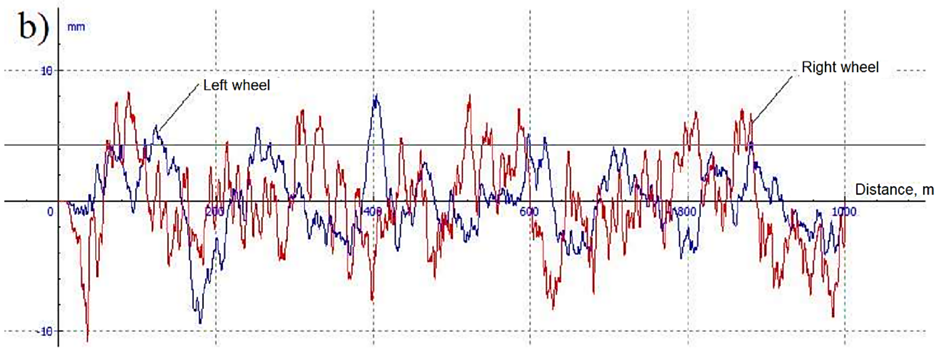

Fig. 5b. Horizontal irregularities of the modeled track

In wheel/rail interactions, two parameters are often analyzed: the Nadal criterion and Sperling's comfort index. The Nadal criterion is widely used for derailment. It takes into account the profile of the wheelset wheel, the contact angle and the coefficient of friction, but it does not take into account the longitudinal forces and the angle of the curve at which it is moved. This criterion describes traffic safety. Another issue is passenger comfort. Passenger comfort is described by Sperling's comfort index [21].

3. SPERLING'S COMFORT INDEX CALCULATION

Free and forced oscillations occur during the movement of a vehicle on a railway track at the respective speed. Forced oscillations appear due to unevenness of the railway track or damaged vehicle wheels (flats, crumbles). Such defects cause the forced oscillations of vehicle bogies and their impact on the car body is transmitted via primary and secondary suspensions. The recurrence of these oscillations is called vehicle vibration and can affect the comfort of passengers adversely.

In passenger rolling stock, passenger comfort performance is a particularly sensitive issue. Vibrations of different frequencies affect the human body differently; thus, it is necessary to look at vibration frequencies when studying irrational phenomena. In research, it is important to assess the fact that vibrations affect a person in various aspects: frequency of vibrations, their amplitude, duration, noise level, air humidity and temperature [15, 21]. It has historically been the case that Sperling's comfort index is commonly used to assess the effects of vibration on passenger comfort. [22]. In any case, the investigation starts with the choice of the track macrogeometry.

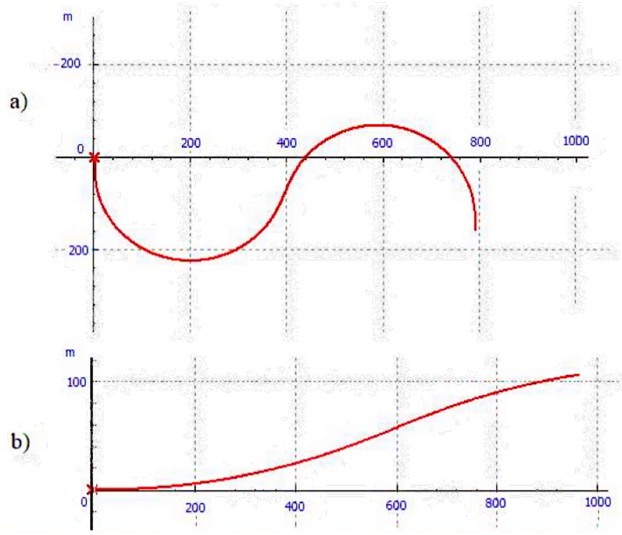

Fig. 6. Track curve geometries of the modeled S type: a) when R = 200 m and b) when R = 2900 m

$$W_Z = \left(\sum_{i=1}^{n_f} W_{Z_i}^{10}\right)^{\frac{1}{10}},$$

where

$$W_{Z_i} = \left[\alpha_i^2 \, B\,(f_i)^2\right]^{\frac{1}{6.67}}, \quad (1)$$

where a is the acceleration, cm/s^2, f is the frequency of vibration, Hz, and B(f) is the coefficient estimating the frequency and direction of oscillations as follows:

$$B(f) = k\sqrt{\frac{1.911\,f^2 + (0.25\,f)^2}{(1-0.277\,f^2)^2 + (1.563\,f - 0.0368\,f^3)^2}}, \quad (2)$$

where k = 0.737 if oscillations are horizontal and 0.588 if oscillations are vertical. The values of the indicators are calculated on the basis of formulas (1) and (2), which are used to assess the comfort quality of the rolling stock passengers.

Sperling's comfort index in lateral and vertical directions at different speeds was calculated in different track sections during the study. The obtained values of indicators are shown in Figs. 7-12.

The lateral and vertical oscillations of rolling stock are not sufficiently correlated to be considered as a coherent system [23]. In this study, although this is not emphasized, vertical and lateral oscillations are investigated separately.

The charts provided in Fig. 7 show that Sperling's comfort index values were lower in the 200 m radius curve in the vertical direction for the model with independently rotating wheels compared to the model with the integral wheelset only at a speed of 75 km/h. At a maximum speed of 90 km/h, the model with independently rotating wheels reached a Sperling's comfort index value of 1.97; the model with the integral wheel reached a Sperling's comfort index value of 1.87 at the same speed. The charts presented in Fig. 8 show that Sperling's comfort index values were lower in the 200 m radius curve in the lateral direction for the model with independently rotating wheels compared to the model with integral wheels set from 80 km/h to 90 km/h speed (90 km/h is the speed limit for the model with independently rotating wheels due to the threshold value of the Nadal criterion reached). At 90 km/h speed, the model with independently rotating wheels reached a Sperling's comfort index value of 2.43 and the model with the set of integral wheels reached a Sperling's comfort index value of 2.48. The charts presented in Fig. 9 show that Sperling's comfort index values were similar or the same in the 2900 m radius curve in the lateral direction for the model with independently rotating wheels and the model with the set of integral wheels from 170 km/h to 200 km/h (200 km/h is the speed limit for the model with independently rotating wheels due to the threshold value of the Nadal criterion reached).

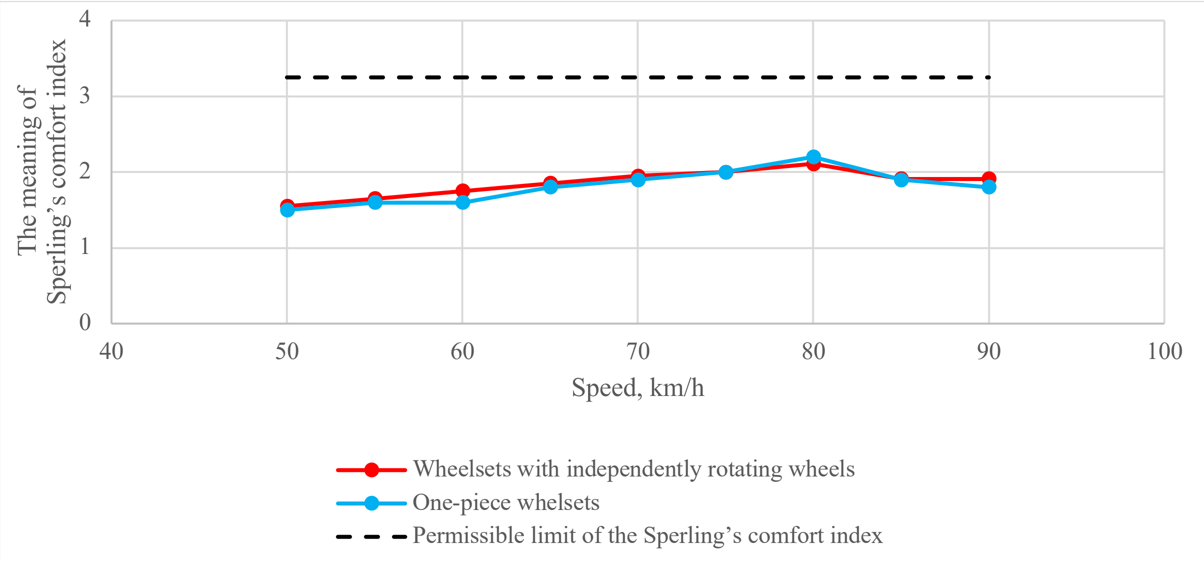

Fig. 7. Sperling's comfort index values in the vertical direction in the 200 m radius curve

At a speed of 200 km/h, the model with independently rotating wheels reached a Sperling's comfort index value of 2.51 and the model with the integral wheelset reached a Sperling's comfort index value of 2.49. The charts provided in Fig. 10 show that the model with integral wheelsets and the model with independently rotating wheels reached permissible values of Sperling's comfort index only in the 2900 m radius curve in the lateral direction: the model with independently rotating wheels reached permissible values at a speed of 185 km/h and the model with the integral wheelset reached permissible values at a speed of 210 km/h. The charts presented in Fig. 11 show that Sperling's comfort index values were similar or the same in the straight track section in the lateral direction for the model with independently rotating wheels compared to the model with the integral wheelset from 180 km/h to 210 km/h (210 km/h is the speed limit for the model with independently rotating wheels due to the permissible value of the Nadal criterion reached). At a speed of 210 km/h, the model with independently rotating wheels reached a Sperling's comfort index value of 2.25 and the model with integral wheelsets reached a Sperling's comfort index value of 2.24. The charts presented in Fig. 12 show that Sperling's comfort index values were lower in the lateral direction in the straight track section for the model with independently rotating wheels compared to the model with the integral wheelset only at a speed 210 km/h (210 km/h is also the speed limit for the model with independently rotating wheels due to the permissible value of the Nadal criterion reached). At a speed of 210 km/h, the model with independently rotating wheels reached a Sperling's comfort index value of 2.98 and the model with the integral wheelset reached a Sperling's comfort index value of 3.05.

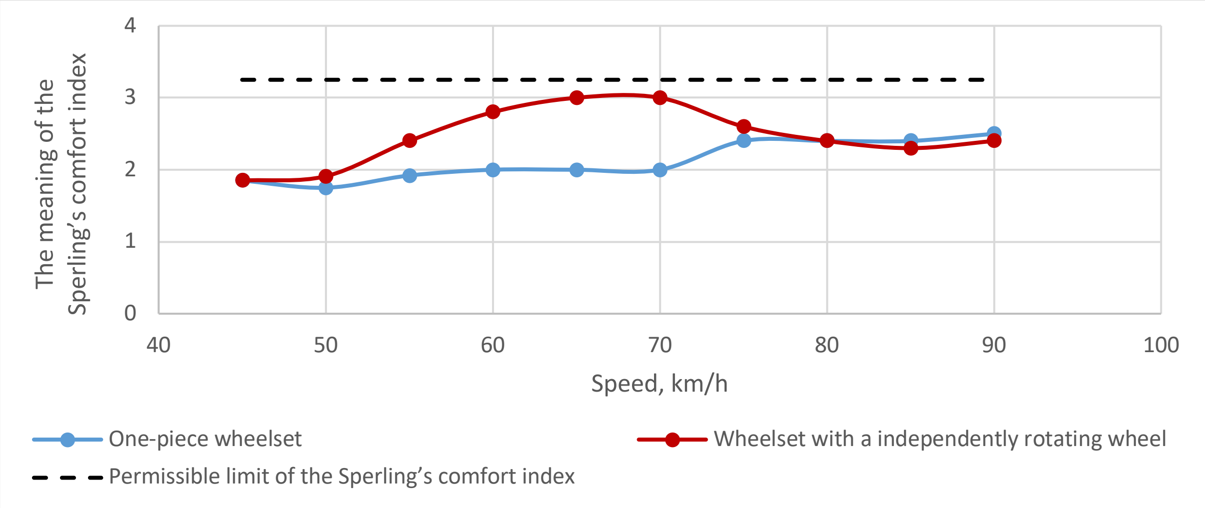

Fig. 8. Sperling's comfort index values in the lateral direction in the 200 m radius curve

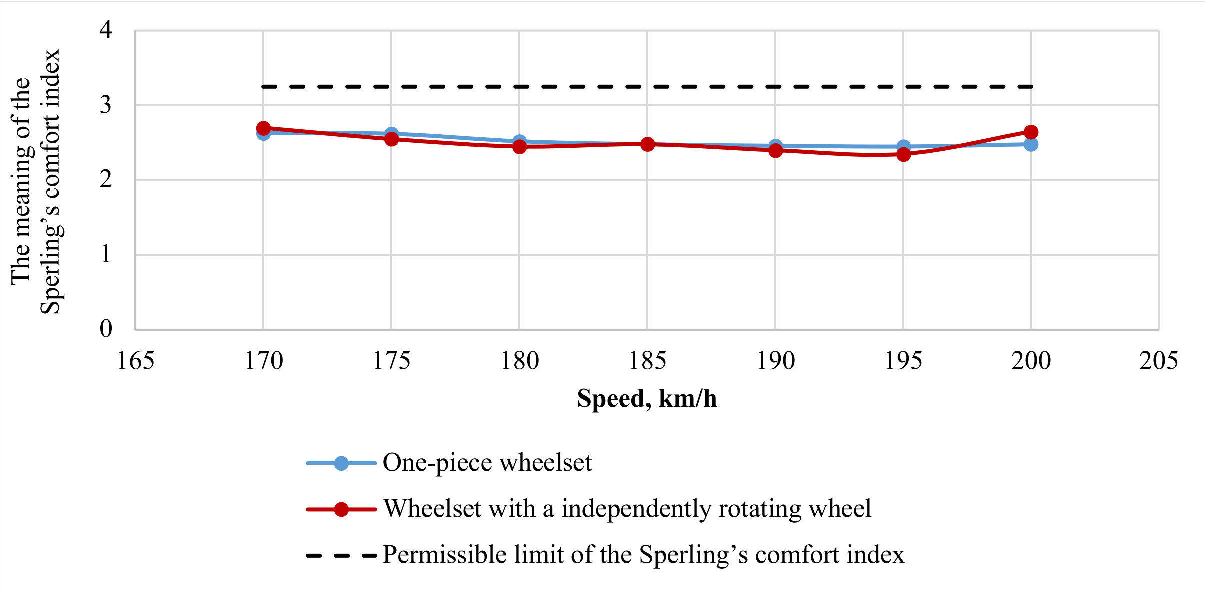

Fig. 9. Sperling's comfort index values in the vertical direction in the 2900 m radius curve

4. CONCLUSIONS

It is possible to compare the dynamic characteristics of rail vehicles with integral wheelsets and with wheelsets with independently rotating wheels by comparing Nadal criterion values; however, the comfort cannot be assessed by this criterion. Sperling's comfort index can be used to assess the comfort.

Studies of Sperling's comfort index values show that there are no huge differences in the significance of Sperling's comfort index for the dynamics in the vertical direction when comparing a passenger car with integral wheelsets and wheelsets with independently rotating wheels both when the vehicle runs in curves and in a straight section.

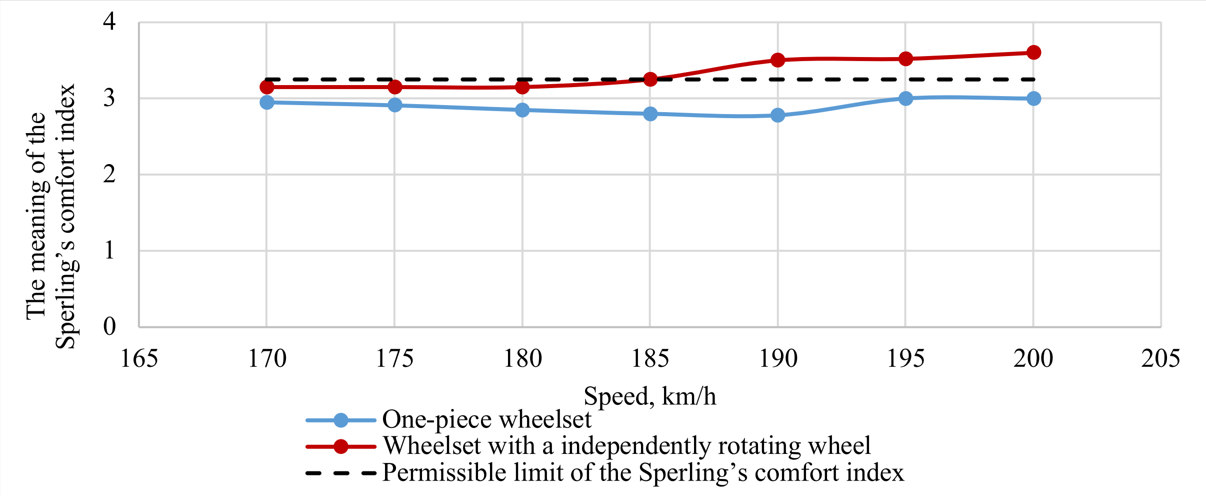

Fig. 10. Sperling's comfort index values in the lateral direction in the 2900 m radius curve

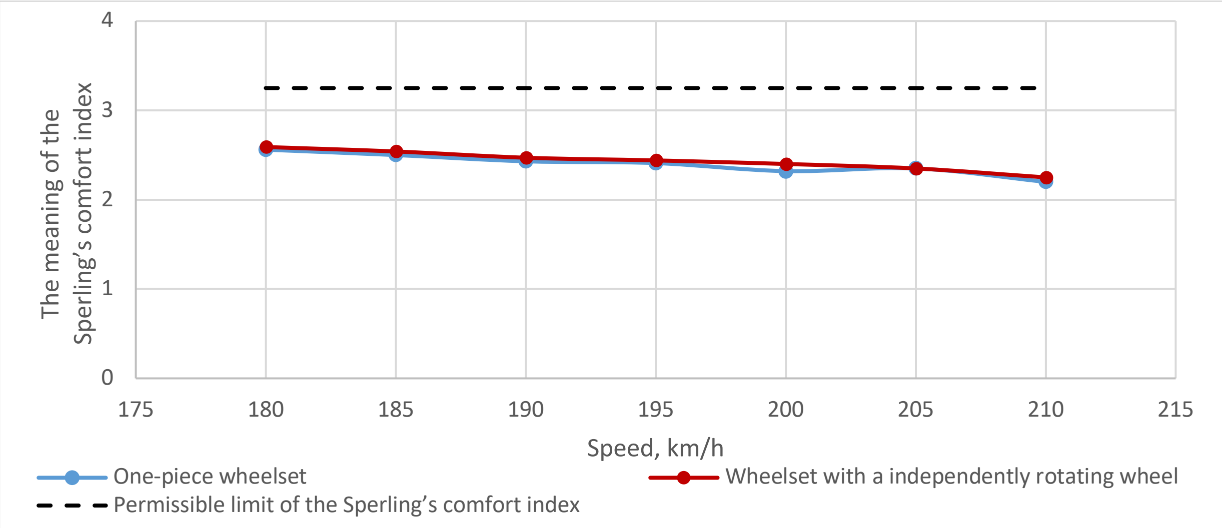

Fig. 11. Sperling's comfort index values in the vertical direction in the straight section

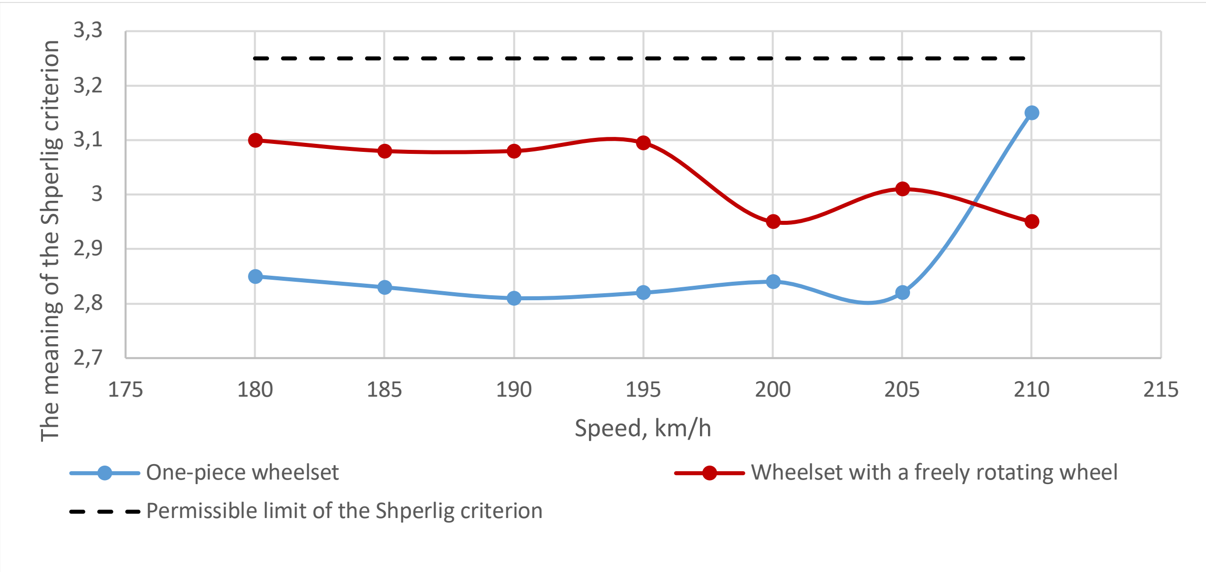

Fig. 12. Sperling's comfort index values in the lateral direction in the straight section

During the study of the 2900 m radius curve, Sperling's comfort index values in the lateral direction exceed the permissible values at a vehicle running speed of 180-190 km/h.

It is necessary to change wagon suspension stiffness and damping parameters to achieve better results for the model with independently rotating wheels.

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