TRANSPORT PROBLEMS 2022 Volume 17 Issue 1
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2022.17.1.18

Keywords: railway; Nadal criterion; Sperling‘s comfort index, running gear, independently rotating wheels

Gediminas VAIČIŪNAS[1]*, Stasys STEIŠŪNAS[2], Gintautas BUREIKA[3]

ADAPTATION OF RAIL PASSENGER CAR SUSPENSION PARAMETERS TO INDEPENDENTLY ROTATING WHEELS

Summary. This study aimed to adjust the rail passenger car running gear parameters by adapting them to independently rotating wheels. The most important aspect was the safety of the passenger car running in terms of derailment; thus, the values of the Nadal criterion were calculated first. Another aspect to consider is passenger comfort based on the values of Sperling's comfort index according to the rail passenger car speed. The modes of suspension behaviour during operation were considered in two typical conditions: on a straight track section and on a curve with a 200-m radius. Calculations were performed using Universal Mechanism software. The results are interpreted in the paper, and the final conclusions of this study are given.

1. INTRODUCTION AND LITERATURE REVIEW

The idea of using independently rotating wheels (IRWs) in rolling stock originated to reduce wheel surface wear. The wear of the wheel surface of rolling stock is a serious problem of rolling stock operation and has been given much attention in the authors' research work [1]. The problems associated with the independently rotating wheels of rail vehicles arise not only in the international scientific discussion, but the specific standards have also been developed in this regard [2]; thus, the idea is not very innovative. However, research on the dynamic properties of rolling stock with independently rotating wheels continues [3]. An important issue is driving rolling stock on rail tracks [4], as a solid wheelset ensures the stability of rolling stock running. The issue of a rational rail wheel running conical surface design is also significant [5]. When examining passenger rolling stock, it is important to keep in mind the passenger's comfort, which has been studied by German scientist Sperling since the middle of the 20th century [6]. Later, other scientists studied the effects of vibrations according to their direction [7] and the characteristics of the rolling stock running gear and body [8], while others have assessed the technical conditions of rolling stock [9]. Studies [10, 11] have shown that when the wheels of a passenger car rotate independently, the value of the Nadal criterion reaches the limit values faster than when using solid wheelsets. Better values for Sperling's comfort index (SCI) could also be obtained, requiring the optimization of the passenger car's suspension parameters.

Wheelsets are critical elements of the running gear of a passenger car. They are designed to guide the movement of the rail vehicle along the rail track and the perception of all loads transmitted from the car running gear to the rails during wheelset rotation. When operated under difficult loading conditions, wheelsets must be highly reliable since the safety of train traffic largely depends on them. Therefore, they are subject to special, increased requirements in terms of their design, manufacture, and maintenance. The design and technical condition of the wheelsets affect the smoothness of the car ride,

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[1] Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania; email: gediminas.vaiciunas@vilniustech.lt; orcid.org/0000-0002-5584-9779

[2] Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania; email: stasys.steisunas@vilniustech.lt; orcid.org/0000-0001-9278-2561

[3] Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania; email: gintautas.bureika@vilniustech.lt; orcid.org/0000-0003-3934-0005

* Corresponding author. E-mail: gediminas.vaiciunas@vilniustech.lt

the magnitude of the forces arising from the interaction of the car wheelsets and the rails, and the car's resistance to movement [3].

When used in modern modes of operation of railways and extreme environmental conditions, the wheelset of the passenger car must meet the following basic requirements: sufficient strength while having a minimum unsprung mass to reduce the tare of the rail vehicle and reduce the direct impact on the track and elements of the car when passing rail track irregularities; sufficient elasticity to reduce the noise level and mitigation of shocks that occur when the passenger car moves along the track; and, together with the axle boxes, possibly provide less resistance during the movement of the passenger car and increase elements' resistance to wear during operation [1].

When the rolling stock moves along curved sections of a track with a small or medium radius, significant additional forces of resistance to movement arise, caused by the action of centrifugal forces and the peculiarities of the contact between the wheelsets and rails when they fit into track curves. This leads to an increase in the interaction forces of the wheel-rail contact and, as a result, in their wear and energy loss for train running. The outer rail is elevated to compensate for centrifugal forces by facilitating fitting into track curves. Also, wheels with a conical shape of the running surface of the tread are used, which allows the wheels to pass different distances along the outer and inner rails of the track due to differences in the diameters of the wheels where they contact the rails. The higher the taper of the surface of the wheels, the easier it is to fit the wheelset into small radius curves. However, at the same time, the dynamic performance of the rolling stock deteriorates as it moves along straight sections of the track due to the occurrence of intense wobbling oscillations. Thus, the taper of the wheel rims is limited by the need to ensure the stability of the movement of the vehicle on straight sections of the track. Thus, in small radius curves, it is not sufficient for the free fitting of wheelsets without slipping. As the creepage velocities increase, so do the creep forces and the contact angle of the wheels on the rails. These factors increase the intensity of wear of the wheel flanges and the inner side surfaces of the rails [2].

In addition, the smooth running of passenger cars depends significantly on the technical condition of the running gear components. One of the most important elements of a car's suspension is the components based on elastomers [12]. Their characteristics and strength affect the reliability and durability of the entire suspension system. Another important element is the journal bearings, the operation of which is crucial for the stable and smooth running of the vehicle's wheelsets [13, 14]. The uninterrupted operation of the running gear of the car can be ensured by timely and high-quality maintenance, as well as by assessments of the influence of the nature of the dynamic force on the service life of these elements of the running gear.

The scientific literature provides many examples of how the parameters of freight wagons are examined. The vibration properties of freight wagons are radically different when the wagon is empty and loaded. However, in a passenger car, the problem is less acute [15]. Because human comfort is subjective, fuzzy methods are sometimes used in research. Also, the dynamic characteristics of a railway passenger car depend on the car's overall bogie design. Therefore, examples of new car bogie design concepts can be found in the literature. The majority of passenger cars are still standard cars, and the suspension parameters of coaches are adjusted to improve safety and comfort and reduce structural fatigue. The human body and the effect of vibrations on its parts have been examined [15].

2. CRITERIA FOR EVALUATING THE DYNAMICS OF A PASSENGER RAILWAY CAR AND RESEARCH METHODOLOGY

In any innovation related to the running gear of rolling stock, it is important to assess its impact on the dynamic behaviour of the rolling stock. These influences are interpreted inversely in different research papers, but some key points are standard. This investigation assesses passenger car dynamics using the Nadal criterion and SCI.

The Nadal criterion is normally used to evaluate wheel and rail sideways in terms of derailment. The circular shape, angle of contact between the rail and the wheel, and the nature and coefficient of friction are taken into account. However, track profile parameters such as curves or gradients are not considered.

This criterion describes track safety (precisely, the stability of rolling stock). Another important and interesting issue is the comfort of rail passengers. Researchers usually describe passenger comfort using SCI, a parameter developed for this purpose.

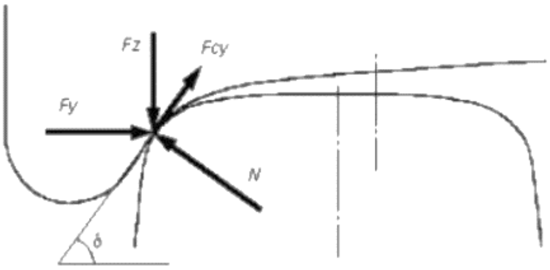

Fig. 1. Wheel-rail contact forces

Wheel-rail contact forces are shown in Fig 1. The Nadal criterion is calculated according to the formula [10]:

$$q_0 = \frac{F_y}{F_z} = \frac{\tan\delta - \mu_y}{1+\mu_y \cdot \tan\delta}; \tag{1}$$

where $\mu_y = \frac{F_y}{N}$; F_z – vertical force; F_y – horizontal force; N – normal force; δ – the angle of contact.

When a railway wagon is running at the appropriate speed, therefore forced oscillations of the car body occur. Forced oscillations occur due to railway inequality or damaged wheelsets (passenger car wheel failures are the subject of a separate investigation). Such defects cause forced oscillations of the bogies of the rolling stock, and their effects on the passenger car are transmitted through the suspension (in the passenger car, the suspension consists of the primary and the secondary suspension).

The systematic repetition of these mechanical oscillations during the rail vehicle's running on railway rails is called the vibration of a car body and usually reduces the comfort of passengers.

Vibrations significantly impair passengers' well-being (and sometimes their health) and reduce the competence of passenger service personnel. Therefore, scientists understand the need for various techniques to assess the intensity of vibration and its harmful effects on humans. Different human bodies respond differently to vibration frequencies. It is necessary to consider the vibration frequencies and the distribution of amplitudes when examining the overall vibration level. The effects of vibration and noise on a railway passenger car and the comfort of the passenger during their journey can be comprehensively assessed by examining the entire set of relevant parameters (e.g. the noise level, frequency, and amplitude of vertical and horizontal vibrations) [4, 10].

SCI can be used to assess the vibration level of a passenger car and passenger comfort [11]:

$$W_Z = \left(\sum_{i=1}^{n_f} W_{Z_i}^{10} \right)^{\frac{1}{10}}; \tag{2}$$

$$W_{z_i} = \left[a_i^2 B(f_i)^2 \right]^{\frac{1}{6.67}}, \tag{3}$$

where a – passenger car body acceleration, cm/s^2; f_i – passenger car body vibration frequency, Hz; $B(f_i)$ – coefficient of vibration frequency and the vibration direction of oscillation affecting the welfare of the passenger:

$$B(f) = k\sqrt{\frac{1{,}911 f^2 + (0{,}25 f^2)^2}{(1 - 0{,}277 f^2)^2 + (1{,}563 f - 0.0368 f^3)^2}}. \tag{4}$$

In the above equation, $k = 0.737$ for horizontal oscillations and 0.588 for vertical oscillations. The smooth running performance of the passenger cars – calculated on the basis of (2) to (4) – is compared with their permissible values (the permissible limits of SCI values are shown in Figs. 11-14). Based on the results of the comparison, the comfort quality of passenger rolling stock was finally assessed.

3. PASSENGER CAR SUSPENSION PARAMETER MODIFICATIONS

The software package Universal Mechanism (UM) was used for the calculations. Passenger car modelling assumes that all bodies are rigid and can move along the X, Y, and Z axes. For computer simulations in the UM passenger car model, all running gear elements were adapted only for solid wheelset types. The passenger car model has left without any suspension elements with IRWs except for the suspension frame. As can be seen from the general view of the structure in Figure 2, a suspension with IRW enabled was modelled using the same design and with the same parameters as in the passenger car model with solid wheelsets.

Vertical and horizontal root mean square (RMS) accelerations of the passenger car depend on the stiffness parameters of the suspension. The corresponding dependencies are shown in Figures 4-8.

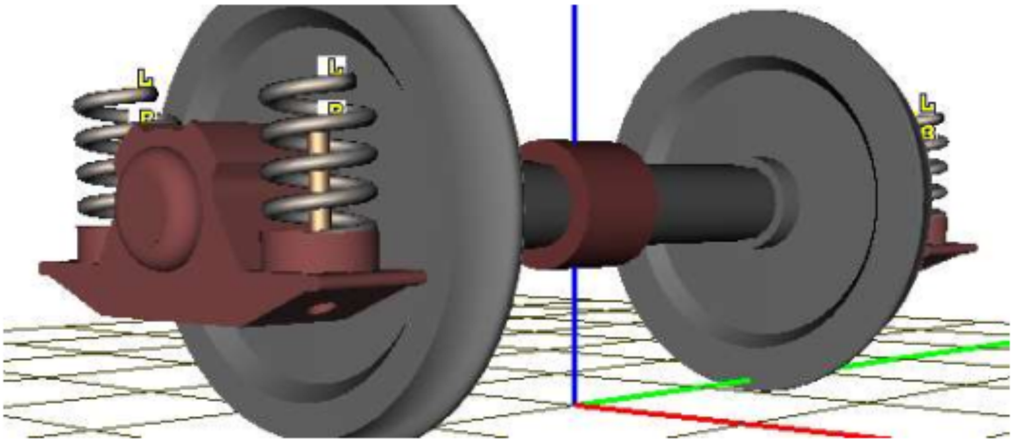

Fig. 2. The wheelset model with IRW

The main suspension stiffness parameters of the passenger car model are presented in Table 1.

Table 1

The main suspension parameters of the passenger car model

Type of suspension	Direction	Value of stiffness, N/m
Primary	lateral	$1.1 \cdot 10^6$
Primary	vertical	$1 \cdot 10^6$
Secondary	lateral	$2 \cdot 10^5$
Secondary	vertical	$9.5 \cdot 10^5$

The track gauge is 1520 mm, and the UIC60 rail profile is used for the simulation. The horizontal and vertical irregularities of the track used for this simulation are shown in Figure 3.

According to data from Figs. 4 and 5 (based on minimal car body accelerations), the primary suspension stiffness values of a vertical stiffness of 900 MN/m and a horizontal stiffness of 600 MN/m are appropriate.

According to data from Figs. 6 and 7, the appropriate secondary suspension stiffness values are a vertical stiffness of 1200 MN/m and a horizontal stiffness of 220 MN/m.

Figs. 4-8 show that the parameters of the standard passenger car suspension are adapted to the solid wheelset. Therefore, these parameters need to be adjusted when using independently rotating wheels. The most appropriate values for these parameters are given in Table 2.

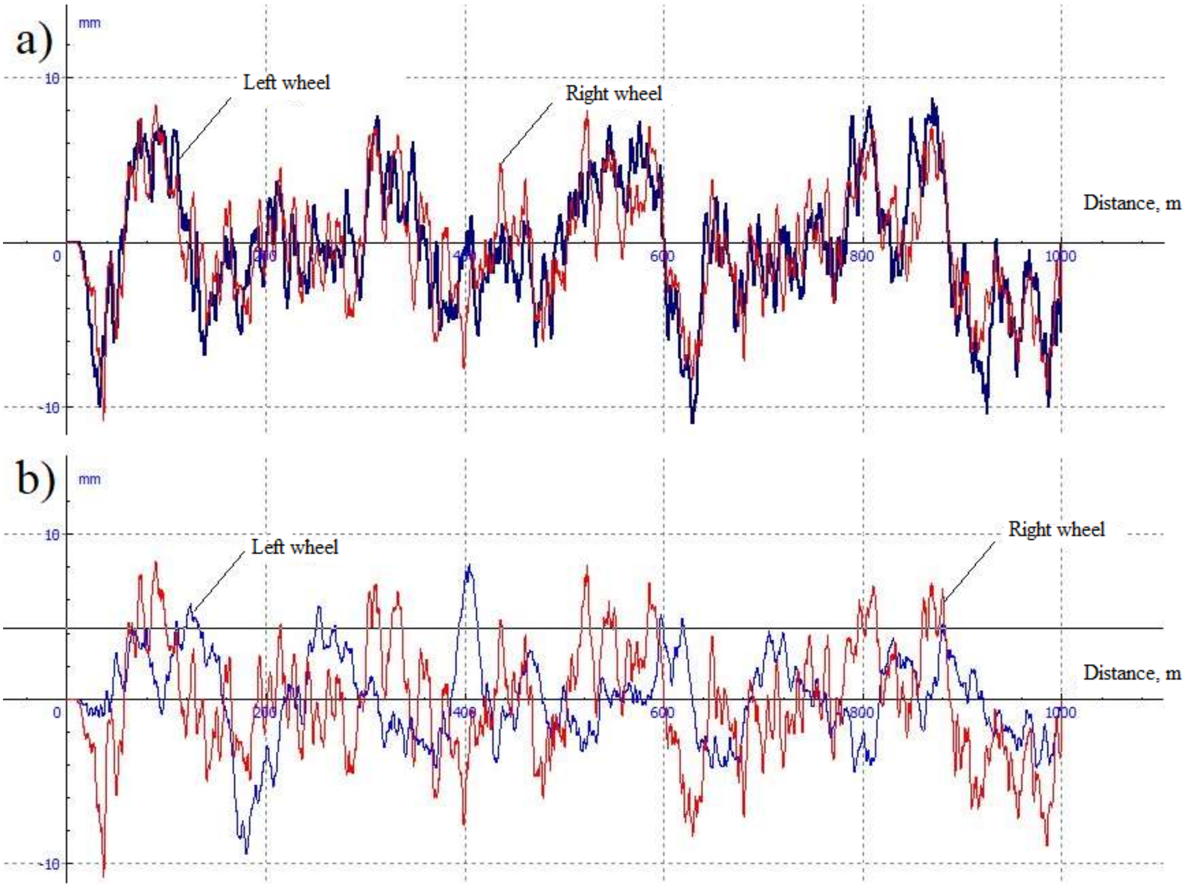

Fig. 3. Modelled track irregularities: a) vertical track irregularities; b) horizontal track irregularities.

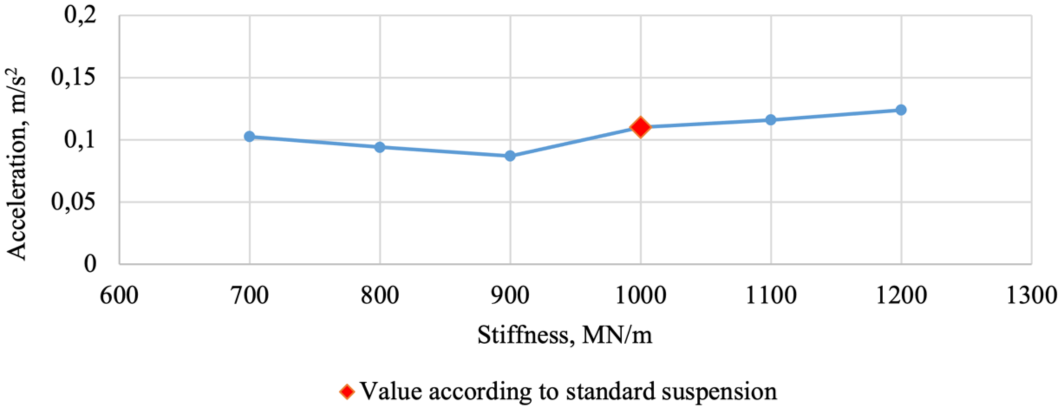

Fig. 4. Dependence of RMS car body accelerations on suspension vertical stiffness parameters (primary suspension, running speed – 210 km/h)

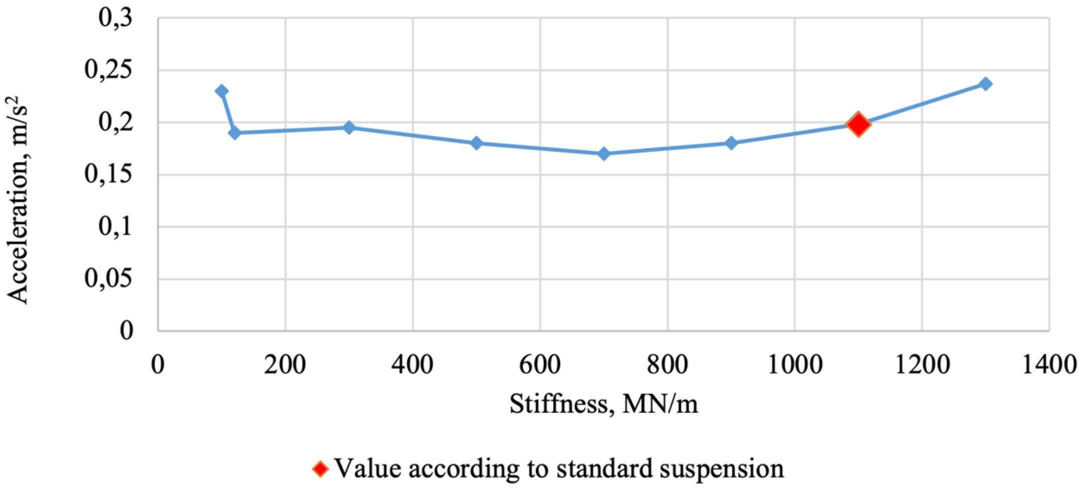

Fig. 5. Dependence of RMS car body accelerations on suspension horizontal stiffness parameters (primary suspension, running speed – 210 km/h)

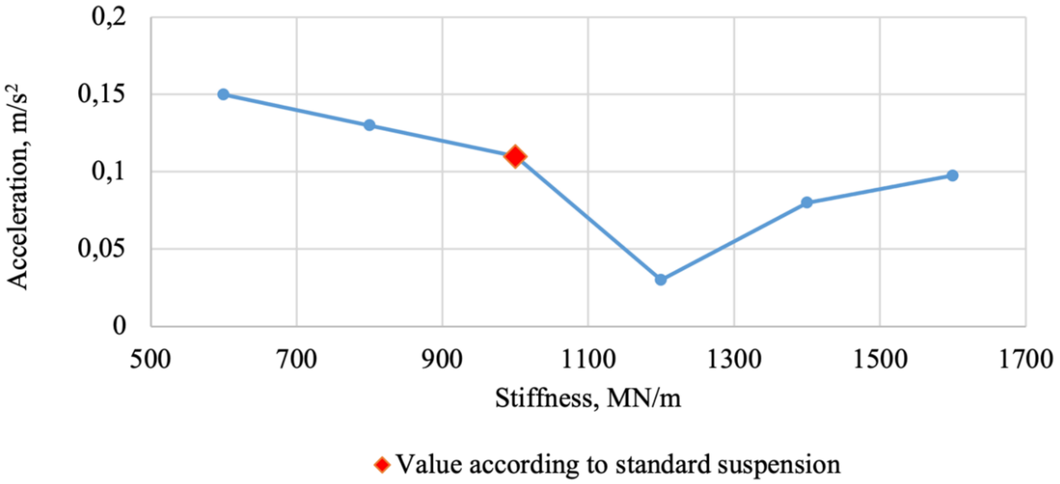

Fig. 6. Dependence of RMS car body accelerations on suspension vertical stiffness parameters (secondary suspension, running speed – 210 km/h)

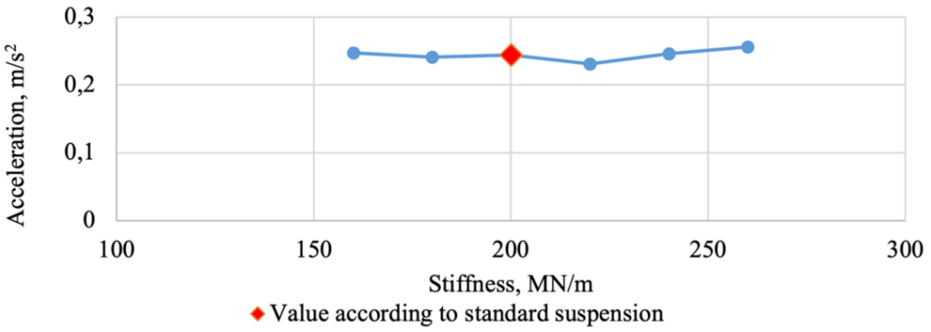

Fig. 7. Dependence of RMS car body acceleration on suspension horizontal stiffness parameters (secondary suspension, running speed – 210 km/h)

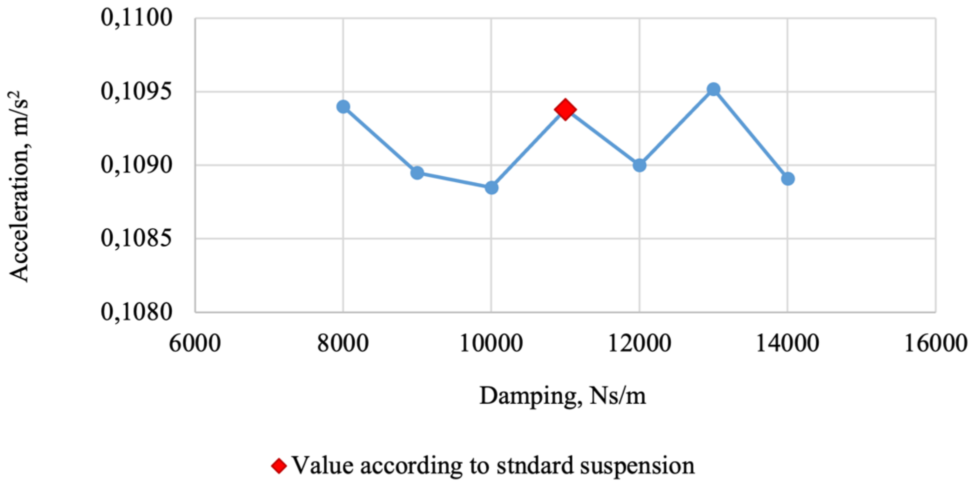

Fig. 8. Dependence of RMS car body accelerations on suspension damping parameters (running speed – 210 km/h)

Table 2

Adjusted values of suspension parameters of passenger car

Parameter	Direction	Value
Stiffness of primary suspension, N/m	vertical	$9\cdot10^5$
	horizontal	$6.5\cdot10^5$
Stiffness of secondary suspension, N/m	vertical	$1.2\cdot10^6$
	horizontal	$2.2\cdot10^5$
Damping of primary and secondary suspension, Ns/m		10^4

The data in Table 2 are used in further studies of dynamic behaviour the passenger car.

4. THE RESULTS OF THE STUDY

The most important aspect of this study is to check the safety of the mechanical system in terms of derailment. Therefore, the values of the Nadal criterion are calculated first. The values of the Nadal criterion, according to the passenger car's speed, are shown in the figures below.

Using wheelsets with IRW on a 200-meter radius curve, the value of the Nadal criterion reached the permissible limit at the speed of 95 km/h before the adaptation of the suspension parameters. After the adaptation of the suspension parameters, the Nadal criterion reached the permissible limit at a speed of 105 km/h.

On a straight section, the value of the Nadal criterion reached the permissible limit at a speed of 210 km/h before the adaptation of the suspension parameters and at a speed of 290 km/h after the adaptation. In summary, it can be said that the Nadal criterion value changes according to the speed of the car. Adjusting the passenger car's primary and secondary suspension settings is essential. When using wheelsets with IRWs in a passenger car moving along a curve, the value of the Nadal criterion reached the permissible limit at a speed of 95 km/h before the adaptation of the suspension parameters and at a speed of 105 km/h after the adaptation.

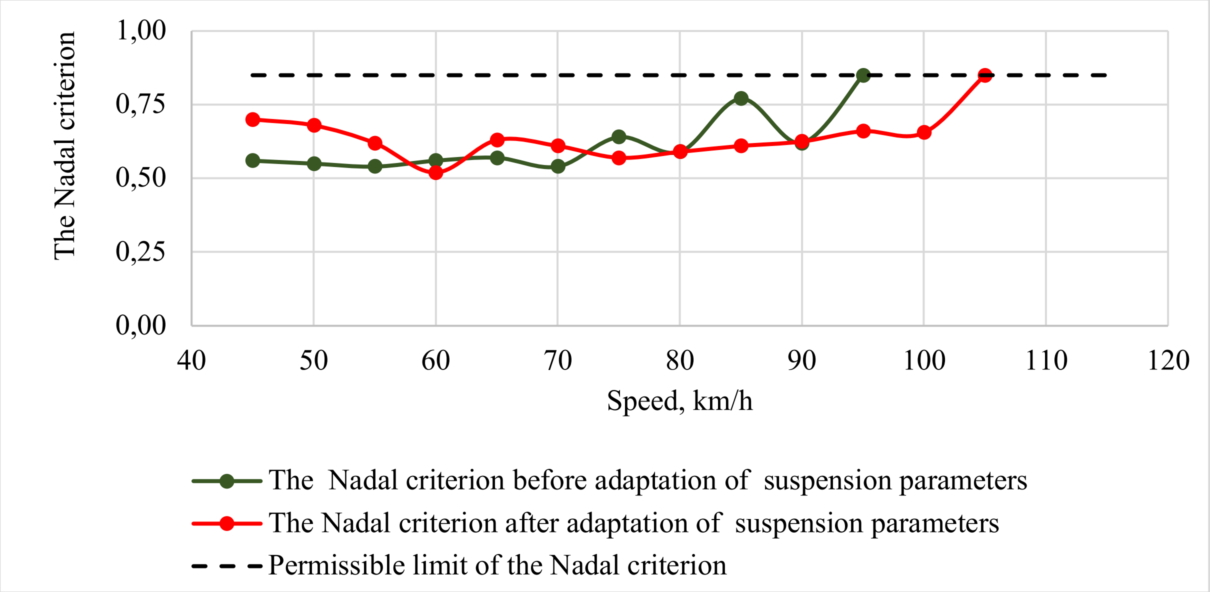

Fig. 9. Dependence of Nadal criterion values on the passenger car's running speed along a curve with a radius of 200 m

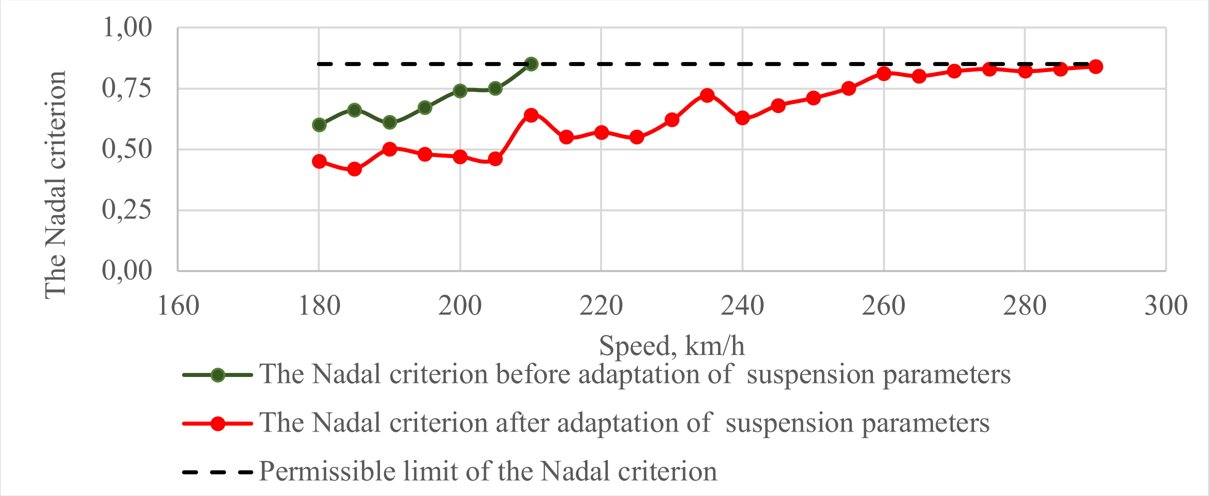

Fig. 10. Values of the Nadal criterion according to the speed of the car in a straight section

Another aspect to consider is passenger comfort. The values of SCI according to the passenger car's speed are shown in the figures below.

Figure 11 shows that SCI values depending on the passenger car's speed on a curve in the vertical direction are similar before and after the adaptation of parameters of the suspension.

Fig. 12 shows that the SCI values change according to the passenger car's speed as it moves along a curve with a 200-m radius.

In both the horizontal and vertical directions, the passenger car's adjusted primary and secondary suspension settings have changed slightly. The peak of the SCI value has shifted from 70 km/h to 60 km/h, but this change is not significant.

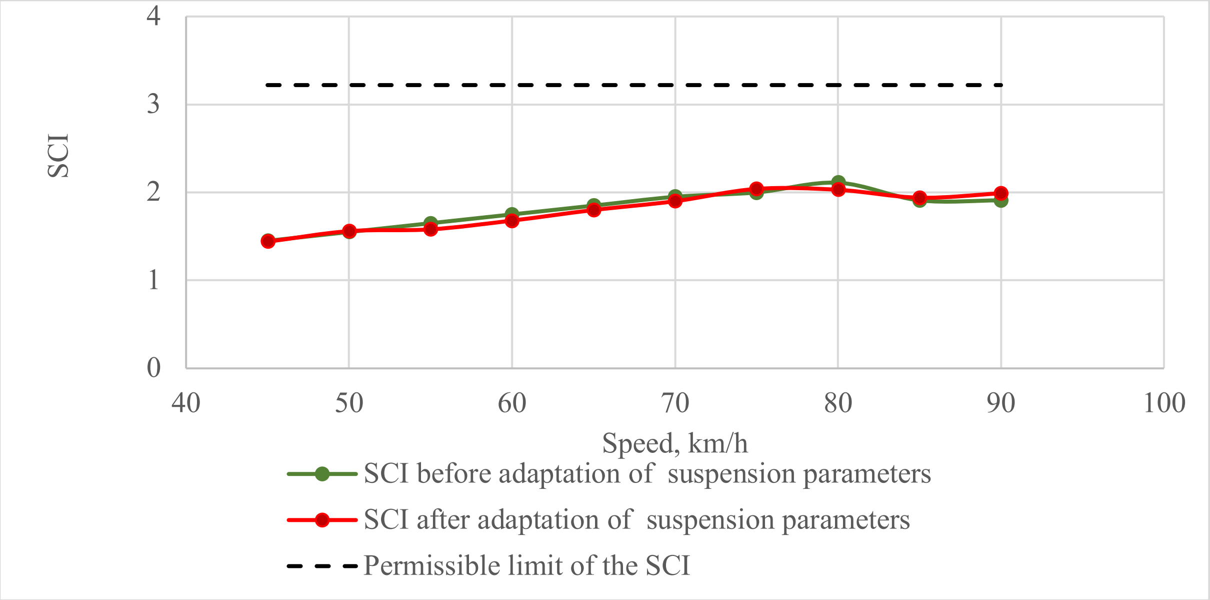

Fig. 11. SCI value according to passenger car's speed along a 200-m radius curve in the vertical direction

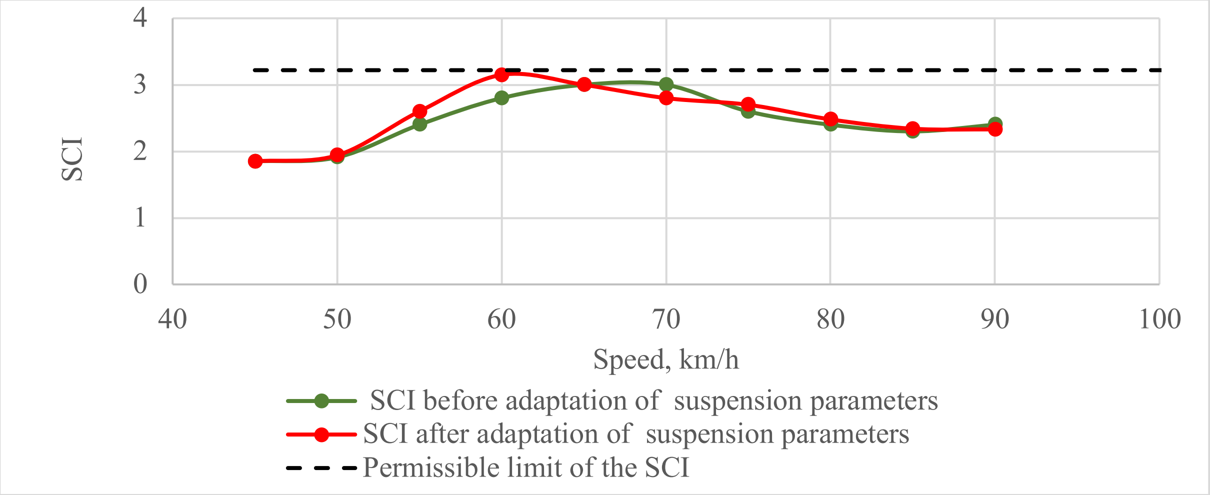

Fig. 12. SCI value according to the passenger car's speed along a curve with a 200-m radius in the horizontal direction

Fig. 13 shows an insignificant change in the values of SCI according to the passenger car's speed in a straight line after the vertical adjustment of the parameters of the suspension of the passenger car.

Next, the values of SCI according to the passenger car's speed in a straight line in the horizontal direction were examined (Figure 14). It can be seen that after the correction of the suspension parameters, the SCI value slightly improved at speeds of 200-210 km/h. The regularities of the change of the SCI values according to the passenger car speed the on the straight section. It was revealed, that after adjusting the primary and secondary suspension parameters of the passenger car changing of SCI in the horizontal and vertical directions were insignificantly.

In summary, adapting the suspension parameters of the passenger car had a particularly significant positive effect in terms of the Nadal criterion. This finding is very important to railway traffic safety.

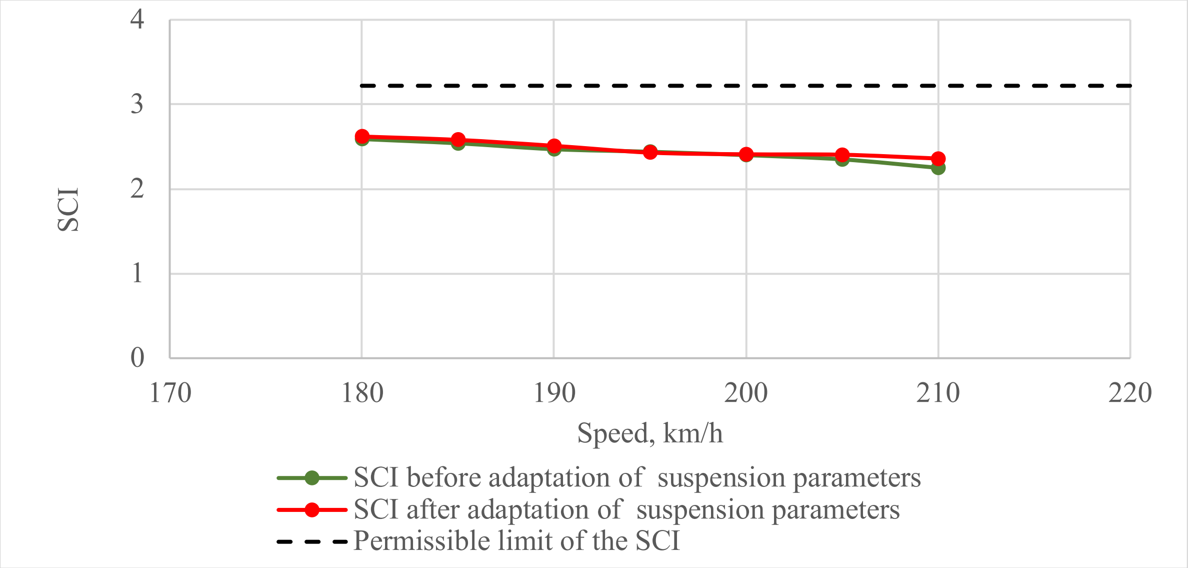

Fig. 13. SCI values according to the passenger car's speed in a straight line in the vertical direction

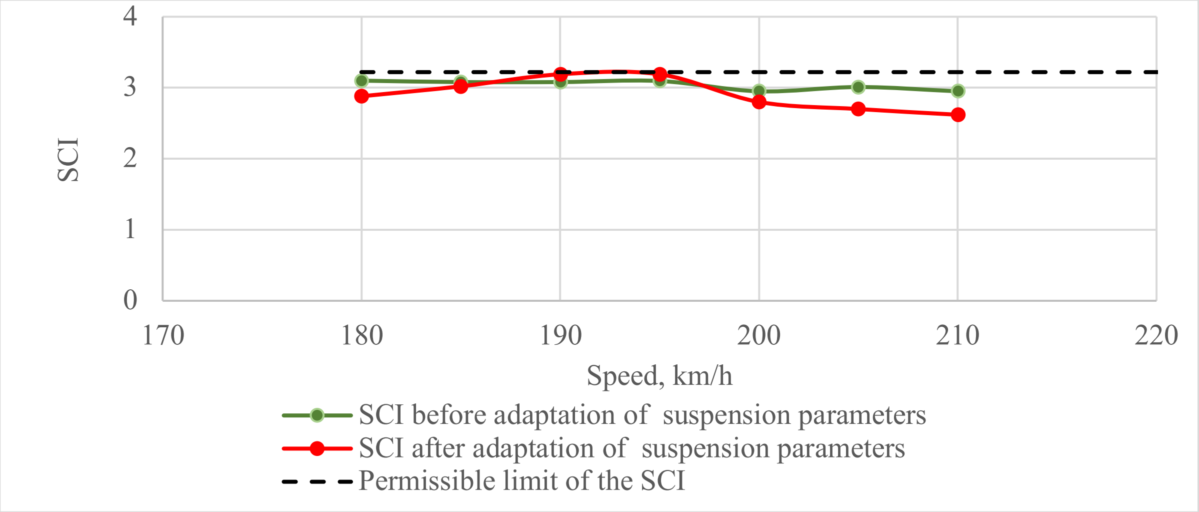

Fig. 14. SCI values according to the passenger car's speed in a straight line in the horizontal direction

5. CONCLUSIONS

1. The dependences of the RMS car body accelerations on the stiffness parameters of the suspension of the passenger car were examined. It was found that the existing (standard) values of the stiffness parameters can be adjusted by adapting to the dynamics of independently rotating wheels.
2. After adjusting the stiffness and damping parameters of suspension of the passenger car, the regularity of the changes of the values of the Nadal criterion and SCI according to speed changed for wheelsets with IRW.
3. The Nadal criterion value changed depending on the speed of the car. Adjusting the passenger car's primary and secondary suspension settings is essential. When using wheelsets with IRWs (when the car travelled along a curve), the Nadal criterion value reached the permissible limit at a speed of 95 km/h before the adaptation of the suspension parameters and at a speed of 105 km/h after the adaptation. When the car travelled in a straight line, the value of the Nadal criterion reached

the permissible limit at a speed of 210 km/h before the adaptation of the suspension parameters and at a speed of 290 km/h after the adaptation.

4. The SCI value's dependence on the speed change after adjusting the stiffness and damping parameters of suspension of the passenger car was most noticeable along a straight section in the horizontal direction. The values improved insignificantly at speeds of 200-210 km/h.
5. The use of IRWs in passenger cars is possible only after modifying the stiffness and damping parameters of suspension.

Acknowledgement

This research was funded by the EU Shift2Rail project GEARBODIES (Grant number: 101013296) under the Horizon 2020/ Shift2Rail Framework Programme.

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Received 04.11.2020; accepted in revised form 14.03.2022