Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 106 **2020**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2020.106.5

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Kardas-Cinal, E. Statistical analysis of dynamical quantities related to running safety and ride comfort of a railway vehicle. *Scientific Journal of Silesian University of Technology. Series Transport*. 2020, **106**, 63-72. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2020.106.5.

Ewa KARDAS-CINAL[1]

STATISTICAL ANALYSIS OF DYNAMICAL QUANTITIES RELATED TO RUNNING SAFETY AND RIDE COMFORT OF A RAILWAY VEHICLE

Summary. This paper investigates the variation of track geometrical parameters that lead to a local increase of specific dynamical quantities of a railway vehicle, possibly beyond their acceptable values. In particular, the changes of track geometry are investigated near track points where the running safety or ride comfort are significantly decreased during the vehicle motion due to track irregularities. The investigated dynamical quantities include the lateral and vertical forces at the wheel-rail contact as well as the acceleration of the vehicle body. The vehicle motion has been simulated using a non-linear model of a passenger car moving along a nominally tangent stiff track with random geometrical irregularities. The relationship between the local track condition and the maxima of the dynamical quantities was investigated with the statistical method proposed by the author. The performed analysis clearly identifies the characteristic variation of track irregularities that leads to a large increase of the investigated dynamical quantities at some track points.

Keywords: railway vehicle dynamics, track irregularities, statistical analysis

[1] Faculty of Transport, Warsaw University of Technology, Koszykowa 75 Street, 00-662 Warsaw, Poland. Email: ekc@wt.pw.edu.pl

1. INTRODUCTION

This paper investigates the dynamical behaviour of a railway vehicle in relation to its running safety and ride comfort. The special emphasis is put on the effect of track condition in the immediate vicinity of track points where large risk of derailment occurs or the ride comfort related to vehicle body vibrations rapidly deteriorates.

A railway vehicle derails when its wheels run off the rails and, in effect, the rails no longer provide the guidance of the vehicle in the lateral direction. Since the risk of derailment is of the ultimate safety concern in the operation of railway vehicles, it has been a subject of many studies in the past (for example, [12]) as well as the topic of ongoing researches [6,10,15,16,19,20,24]. While various scenarios of derailment are possible and the respective criteria have been proposed and are in use [18], one of the earliest relevant works was published by Joseph Nadal in 1896 [17]. The conditions for the derailment by the wheel climb over the rail are determined by lateral (Y) and vertical (Q) forces that act at the wheel/rail contact. The Nadal criterion of safety against derailment gives the limit value of the derailment coefficient Y/Q depending on the friction coefficient and the wheel flange angle at the contact point. This criterion is included in the current railway safety regulations, like the UIC 518 code [23] and the EN 14363 standard [4] used for the evaluation of dynamical vehicle behaviour with the tests of the running characteristics required for acceptance of railway vehicles.

The ride comfort is one of the fundamental issues in transportation. It is a complex notion, which contains a series of components specifying, among others: thermal comfort, acoustic comfort, air quality, and vibrational comfort. The sensations related to comfort depend on various factors characterising, the surroundings in which the passenger of a railway vehicle is in, such as vibrations, temperature, humidity, noise and lighting as well as the passenger's position and the length of time during which the passenger is affected by the aforementioned factors. Comfort level indicators, dependent on one or several physical parameters characterising the passenger's environment, are used for the synthetic evaluation of the ride comfort [7].

One of the most important physical factors that substantially impact the ride comfort is the vibrations to which the passenger is exposed to during the travel. The main parameters determining the comfort related to vibrations are the accelerations experienced by a person travelling in a chosen means of transportation. The usual approach to the evaluation of vibrational comfort is the spectral analysis of the vehicle vibrations. This analysis gives the root-mean-square (rms) accelerations in 1/3–octave frequency bands which are subsequently compared with the relevant limits in each frequency band or used to calculate a synthetic index of vibrational comfort. The former method was implemented in the standard ISO 2631-1:1985 [11], where the frequency-dependent boundaries of reduced comfort, fatigue-decreased proficiency and exposure are given. The current regulations, like the ISO 2631-1:1995 [11] standard and the European standard EN 12299:2009 [3], follow a simpler approach, originally proposed by Sperling [22], where a synthetic comfort index is obtained with the rms accelerations weighted with the frequency-dependent functions [2]. The use of weighting functions in the evaluation of the vibrational comfort is connected to the different sensitivity of the human body to vibrations with different frequencies which are related to resonance frequencies of various parts of the body. The influence of vibrations on the human body also depends on their direction and the body's posture (standing, sitting, lying down). A detailed overview of the influence of vibrations on a human body can be found in Griffin's monograph [7] and in Förstberg's comprehensive PhD thesis [5].

The spectral analysis of vibrations provides its global characteristics that do not properly reflect their local variation due to discrete events. This aspect of vibration comfort is due to the momentary increase of acceleration and the presence of jerks (sudden changes of acceleration). A complex comfort index related to discrete events and depending both on the maximum values of the acceleration and jerk is included in the ISO 2631-1:1995 [11] standard and the European standard EN 12299:2009 [3]. On the other hand, the UIC 518 code [23] gives the limits for lateral and vertical acceleration in the running behaviour of the railway vehicle. In the present work, we follow this latter attitude and investigate the conditions for the occurrence of large values of the vehicle body acceleration.

Investigation of vehicle dynamics, including evaluation of running safety and ride comfort, is often performed with the aid of numerical simulations [8,9,12,14,15,21]. This approach was applied in this work in order to investigate the variation of track geometrical parameters near the track points where a strong increase of Y/Q occurs or the lateral vehicle body acceleration becomes large. The main part of this work is the statistical analysis of the random track irregularities disturbing the vehicle motion and the dynamical responses. This analysis is done in a non-standard way since it is limited to the set of short track sections around these specific track points. In this way, it is possible to determine the characteristic local variation of track irregularities that leads to a local increase of the chosen dynamical responses of a railway vehicle, like Y/Q and the vehicle body acceleration. In particular, the track geometry is investigated near track points where large risk of derailment occurs.

2. METHODS

The reported theoretical and numerical investigations are performed in the following way. We start with a model of a discrete mechanical system representing a railway vehicle – track system. The model is used in numerical simulations of a railway vehicle moving along a track with geometrical irregularities. The obtained simulation results are subsequently analysed with the proposed statistical method for discrete events corresponding to the occurrence of large values of selected dynamical responses.

2.1. Railway vehicle – track model

The present simulation study was performed based on a non-linear model of a railway vehicle with 27 degrees of freedom, which describes a conventional passenger car built of seven rigid bodies: car body, two bogies and four wheelsets with the primary and secondary suspension [14]. The forces at the wheel/rail contact point are determined within Kalker's simplified non-linear theory [13] for rails of UIC60 profile and wheels of S1002 profile.

The vehicle motion has been simulated for a constant velocity v along a nominally tangent stiff track with random geometrical irregularities. The track irregularities include: lateral irregularities y_{w}, vertical irregularities z_{w}, cant (superelevation) θ_{w}, variable gauge ($2l_0$), and they depend on the location x along the track. The problem of track irregularities, their evolution and relation to track settlement was considered, for example, in the paper [1].

The vehicle motion is described with the set of second-order differential equations of the following general form:

$$M\frac{d^2\boldsymbol{q}}{dt^2}+C\frac{d\boldsymbol{q}}{dt}+K\boldsymbol{q}=\boldsymbol{F}[\boldsymbol{q},\,d\boldsymbol{q}/dt,\xi,\,d\xi/dt]\ . \tag{1}$$

Here $\boldsymbol{q}=(q_1,q_2,\ldots,q_{27})$ is the vector of generalised coordinates (independent) of the mechanical system, M – its inertia tensor, C, K – damping and stiffness matrices (describing the vehicle suspension), t – time, while the vector $\xi=(y_{\mathrm{w}},z_{\mathrm{w}},\theta_{\mathrm{w}},2l_0)$ includes geometrical track irregularities which act as kinematic excitations. The right-hand side in Equation 1 is given by the vectors of external forces and torques which both arise due to the forces at the wheel-rail contact points.

2.2. Statistical method for discrete events

During the vehicle motion along the track, the values of dynamical variables can rapidly change at some times (or at the respective track points) which may correspond to discrete events undesired from the point of view running safety or ride comfort. The relation between the local track condition and such discrete events, herein maxima of a dynamical response R_D (like derailment coefficient $|Y/Q|$ or one of the vehicle body accelerations a_{by}, a_{bz}) is investigated with the aid of the following statistical method, which is an extension to the approach presented in [14]. The novel element in the present work is extending the scope of this method to various dynamical responses related not only to the running safety but also to other aspects of running behaviour. In this method, the track irregularities are considered as a function of $u=x-x^{(k)}_{\mathrm{peak}}$ only around several (M) track points $x=x^{(k)}_{\mathrm{peak}}$ (k=1,...,M) at which the dynamical response R_D in question has *local* maxima (or minima) of large value (peaks). The value of a track irregularity $\boldsymbol{\xi}_w$ at a distance u from the peak position is averaged over the set of all M short track intervals near the track points where the peaks of R_D occur.

As a result, the average dependence of this irregularity in the vicinity of the peak locations is obtained:

$$\boldsymbol{\xi}^{\mathrm{av}}_w(u)=\frac{1}{M}\sum_{k=1}^{M}\boldsymbol{\xi}_w(x^{(k)}_{\mathrm{peak}}+u) \tag{1}$$

as a function of the distance u from the peak. Taking this average reveals components of track irregularities $\boldsymbol{\xi}_w$ that are common in all the dependences $\boldsymbol{\xi}_w(x)=\boldsymbol{\xi}_w(x^{(k)}_{\mathrm{peak}}+u)$ around the peak locations. In particular, relevant oscillatory components with the same wavelengths and phase can be extracted. In this way, it is possible to determine the characteristic variation of the track irregularities before the track locations where the peaks of the investigated dynamical response R_D occur.

A similar formula can also be used to determine the average dependences of the vehicle dynamical responses in the vicinity of the R_D peak locations:

$$R^{\mathrm{av}}(u)=\frac{1}{M}\sum_{k=1}^{M}R(x^{(k)}_{\mathrm{peak}}+u) \tag{2}$$

where R is an arbitrary dynamical response, for example, wheelset lateral displacements y_i ($i = 1,2,3,4$) or even the R_D response itself.

3. RESULTS

The simulations were performed for a track section of 4000 m with random track irregularities with standard deviations corresponding to QN1 track class [14]. The presented results correspond to simulation runs at v=160 and 200 km/h. The selected dynamical responses whose peaks are considered are the derailment coefficient Y/Q and the lateral body acceleration a_{yb}.

The ratio Y/Q obtained in simulations for the leading wheelset of the front bogie at v=200 km/h has momentary minima with values less than -1.3 at M = 10 track points. The variations of the following quantities around the Y/Q peak locations: the lateral track irregularity y_w, the lateral wheelset displacement $y_1 - y_w$ with respect to the track centre line and the derailment coefficient Y/Q itself, are shown in Fig. 1. The figure also shows the average dependences of these quantities found with the statistical method described in the previous section.

The obtained average dependences around the peak locations prove clearly that the peaks of Y/Q occur at points where the lateral wheelset displacement is maximal due to local occurrence of enhanced wheelset hunting. As seen in Fig.1, this dynamical behaviour is excited by lateral track irregularities y_w which include – on short track sections, around 30 m long before the Y/Q peak positions – a dominant oscillatory component with wavelength close to the wheelset hunting wavelength, equal to 9 m in the reported case. Thus, it can be concluded that such specific oscillations of lateral track irregularities are responsible for the occurrence of Y/Q peaks.

A similar analysis is done for the lateral body acceleration a_{yb} and its results are presented in Fig. 2. It is found that for the railway vehicles travelling at the speed of v=160 km/h the acceleration a_{yb} has minima lower than $-0.45\,\mathrm{m/s^2}$ at $M = 13$ points $x_{\mathrm{peak}}^{(k)}$ on the considered track of the 4000 m length. At the same number of points ($M = 13$), though lying at different track locations $x_{\mathrm{peak}}^{(k)}$, the acceleration a_{yb} has maxima greater than $0.45\,\mathrm{m/s^2}$. The variations of a_{yb} are very similar on a very short track section (less than 40 m long) in the immediate vicinity of every minimum location $x_{\mathrm{peak}}^{(k)}$. The common variation of a_{yb} around the peak is well represented by the statistical average $a_{yb}^{\mathrm{av}}(x - x_{\mathrm{peak}})$ found with the formula (2). It has the form of local oscillations which have the largest amplitude at the location of the a_{yb} peak.

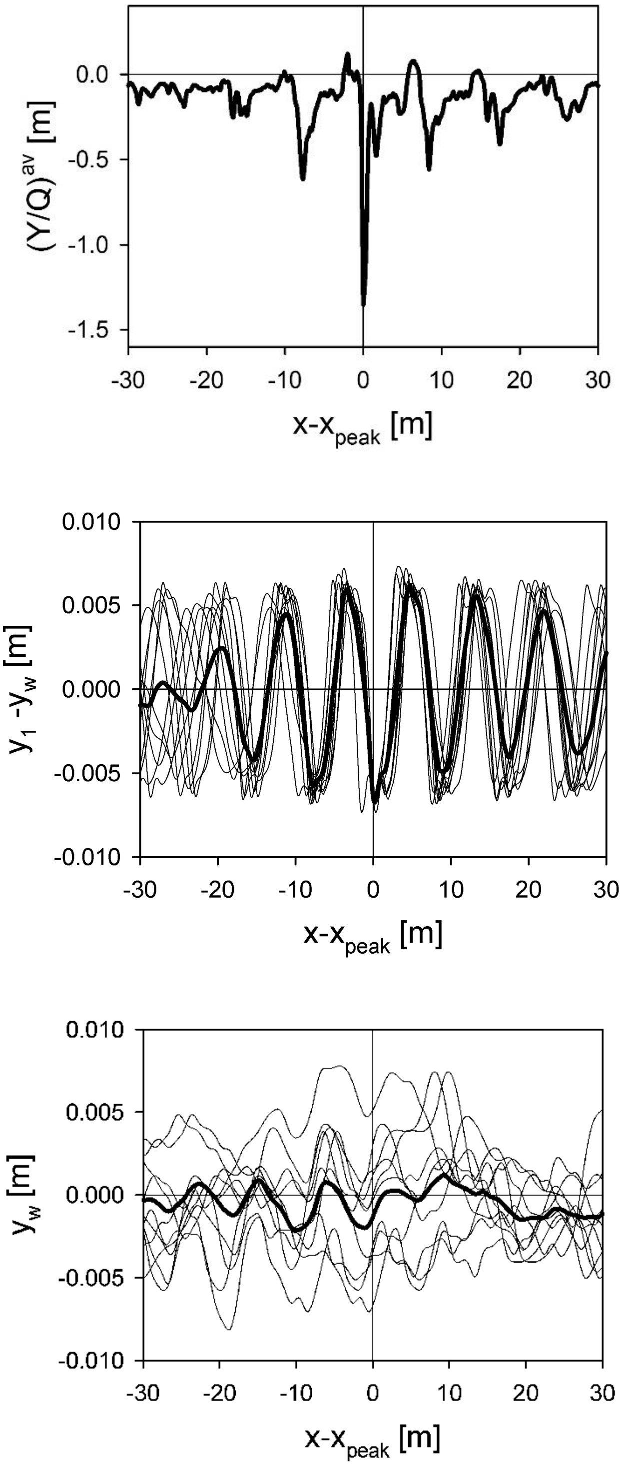

Fig. 1. Derailment coefficient Y/Q, lateral track irregularities y_w and relative lateral displacement of leading wheelset $y_1 - y_w$ versus $u = x - x_{\mathrm{peak}}$ near various $M = 10$ track points where the minima $Y/Q \le -1.3$ occur for the ride velocity $v = 200$ km/h . The bold lines mark the average values y_w^{av}, $y_1^{\mathrm{av}} - y_w^{\mathrm{av}}$, $\left(Y/Q\right)^{\mathrm{av}}$; Equations 1 and 2)

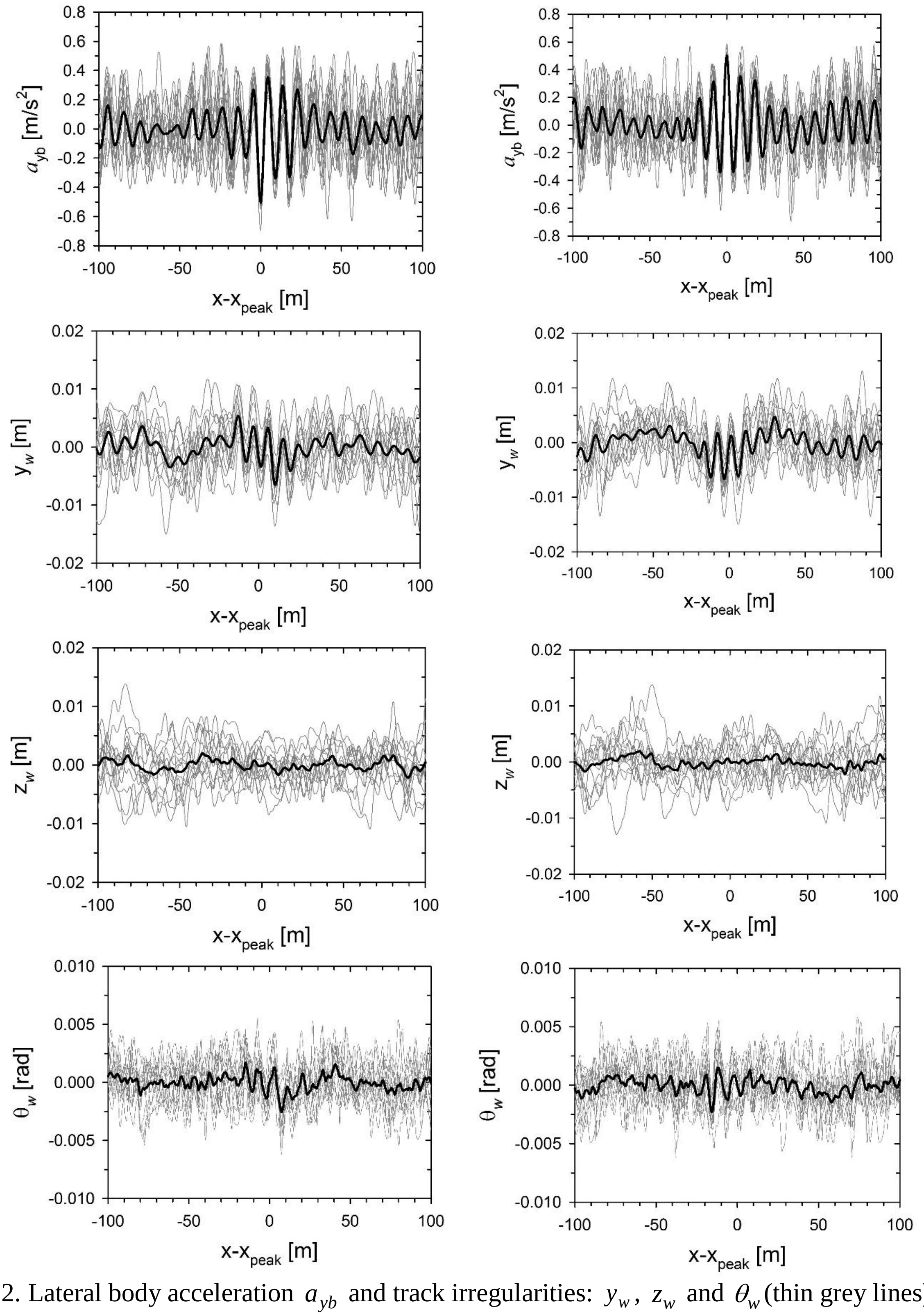

Fig. 2. Lateral body acceleration a_{yb} and track irregularities: y_w, z_w and θ_w (thin grey lines) around the points $x_{\text{peak}}^{(k)}$ $(k = 1,\ldots, M = 13)$ where $a_{yb} < -0.45\,\text{m/s}^2$ (left column) or $a_{yb} > 0.45\,\text{m/s}^2$ (right column) and their averages a_{yb}^{av}, y_w^{av}, z_w^{av}, θ_w^{av} (thick black lines) for v=160 km/h

These oscillations are also present at larger distances from the peak location where the individual dependences $a_{yb}(x-x_{\text{peak}}^{(k)})$ $(k=1,\ldots,M)$ differ significantly but still include a common oscillatory component. The same conclusions apply for the variation of a_{yb} around the locations of the a_{yb} maxima.

The peaks of the lateral body acceleration arise mainly due to the lateral track irregularities. Their average dependence $y_w^{\text{av}}(x-x_{\text{peak}})$ shows enhanced oscillations in the vicinity of the peak and the oscillation wavelength is identical as for the local oscillations of $a_{yb}^{\text{av}}(x-x_{\text{peak}})$ in the same track section around the peak. Another track irregularity which can be a source of the peaks in the lateral body acceleration is variable cant. Indeed, the obtained results show (Fig. 2) that the average cant dependence $\theta_w^{\text{av}}(x-x_{\text{peak}})$ shows clear oscillations of the same wavelength but they are less pronounced than the oscillations of the average lateral track irregularities y_w^{av}. The determined wavelength, around 9-10 m, of the y_w^{av} and θ_w^{av} oscillations is very close to the oscillation wavelength of the wheelset hunting which is known to be almost independent of the ride velocity. Thus, the specific oscillatory components of the track irregularities (lateral and cant) with the wavelength close to the wheelset hunting wavelength are also responsible for the large peaks of the lateral body acceleration. On the other hand, the vertical track irregularities z_w do not play a significant role in occurrence of the peaks of a_{yb} since the average dependence $z_w^{\text{av}}(x-x_{\text{peak}})$ does not show any specific variation in the vicinity of these peaks as seen in Fig. 2.

4. RESULTS

The statistical method previously introduced for investigating the derailment coefficient [14] is now extended to various dynamical responses related not only to the running safety but also to other aspects of running behaviour, like the ride comfort. In particular, alongside the derailment coefficient, vehicle body acceleration is also investigated. The developed method is used to determine characteristic variations of local track irregularities that lead to the occurrence of large peaks of selected dynamical quantities describing a moving railway vehicle. For this purpose, the statistical analysis is limited to a set of short track sections where such peaks occur. This specific statistical method is an efficient means of investigating discrete events that occur during the motion of a railway vehicle along the track with random geometric irregularities.

The performed analysis reveals that the peaks of the derailment coefficient and lateral vehicle body acceleration arise due to local oscillations of lateral track irregularities and cant with wavelengths close to the wavelength of the wheelset hunting. Thus, it is found that specific track irregularities of this form are a common factor that leads to lowering both the running safety and the ride comfort at some discrete times during the vehicle motion. It should be noted that the statistical analysis of discrete events is focused on the local variation of the dynamical responses and the relevant excitations. Therefore, it provides valuable conclusions, which are complementary to the global characteristics of such quantities that are obtained with the spectral analysis, routinely used not only in the evaluation of the ride comfort but also in specific problems of the running safety [14]. The presented statistical method can also be applied to investigate the relationship between the disturbances and dynamical responses in other mechanical systems or dynamical systems in general.

References

1. Chudzikiewicz Andrzej, Józef Droździel, Bogdan Sowiński. 2009. „ Mathematical model of track settlement caused by dry friction in the ballast”. *Archives of Transport* 21(3-4): 25-28. ISSN 0866-9546.
2. Dumitriu Madalina Gheti Marius Alin. 2015. „Evaluation of the ride quality and ride comfort in railway vehicles based on the index Wz”. *ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering*, Tome XIII– Fascicule 3 [August]. ISSN: 1584-2673.
3. EN 12299. 2009. *Railway applications - Ride comfort for passengers - Measurement and evaluation*. European Committee for Standardization.
4. EN 14363.2005. *Railway applications - Testing for the acceptance of running characteristics of railway vehicles - Testing of running behaviour and stationary tests*. European Committee for Standardization.
5. Förstberg Johan. 2000. „Ride comfort and motion sickness in tilting trains - Human responses to motion environments in train and simulator experiments”. PhD thesis, Stockholm, Sweden: Department of Vehicle Engineering, Royal Institute of Technology, ISSN 1103-470X.
6. Grechi Daniele, Elena Maggi. 2018.-„The importance of punctuality in rail transport service: an empirical investigation on the delay determinants”. *European Transport \ Trasporti Europei* 70(2). ISSN: 1825-3997.
7. Griffin Michael J. 1990. *Handbook of Human Vibration*. London: Academic Press Limited. ISBN 978-0-12-303040-5.
8. Haniszewski Tomasz. 2017. “Modeling the dynamics of cargo lifting process by overhead crane for dynamic overload factor estimation”. *Journal of Vibroengineering* 19(1): 75-86. DOI: 10.21595/jve.2016.17310. ISSN: 1392-8716.
9. Haniszewski Tomasz, Damian Gaska. 2017. “Numerical modelling of I-Beam jib crane with local stresses in wheel supporting flanges - influence of hoisting speed”. *Nase More* 64(1): 7-13. DOI: 10.17818/NM/2017/1.2. ISSN: 0469-6255.
10. Iijima Hitoshi, Yoshida Hisashi, Suzuki Kosuke, Yasuda Yoichi. 2014. „A Study on the Prevention of Wheel-Climb Derailment at Low Speed Ranges”. *Quarterly Report of Railway Technical Research Institute: JR EAST Technical Review* 30: 21-24.
11. ISO 2631-1. 1985 and 1997. *Mechanical vibration and shock evaluation of human exposure to whole-body vibration*. *Part 1: General Requirements.* International Organization for Standardization.
12. Iwnicki Simon (Ed.). 2006. *Handbook of Railway Vehicle Dynamics*, Boca Raton: Taylor & Francis/CRC Press. ISBN 9780429129803. DOI: https://doi.org/10.1201/9781420004892.
13. Kalker Joost Jacques.1982. „A Fast Algorithm for the Simplified Theory of Rolling Contact”. *Vehicle System Dynamics* 11(1): 1-13. DOI: https://doi.org/10.1080/00423118208968684.
14. Kardas-Cinal Ewa. 2013. *Bezpieczeństwo i komfort jazdy pojazdu szynowego z uwzględnieniem losowych nierówności geometrycznych toru*. Scientific works of the Warsaw University of Technology. Transport. Z. 94. Warsaw: Warsaw University of Technology Publishing House. [In Polish: *Running safety and ride comfort of railway vehicle in the presence of random geometrical track irregularities*]. ISSN 1230-9265.

15. Ling Liang, Dhanasekar Manicka, Thambiratnam David P., Sun Yan Q. 2016. „Lateral impact derailment mechanisms, simulation and analysis”. *International Journal of Impact Engineering*. 94(1): 36-49. DOI: 10.1016/j.ijimpeng.2016.04.001.
16. Liu Xiang. 2016. „Statistical causal analysis of freight-train derailments in the United States”. *Journal of Transportation Engineering, Part A: Systems* 143(2): 04016001-7. DOI: https://doi.org/10.1061/JTEPBS.0000014.
17. Nadal M.J. 1986. *Theorie de la stabilite des locomotives.* [In French: *Theory of locomotive stability*]. Movement de Lacet, Annales des Mines, Part II 10: 232-255.
18. National Academies of Sciences, Engineering, and Medicine. 2005. *Flange Climb Derailment Criteria and Wheel/Rail Profile Management and Maintenance Guidelines for Transit Operations*. Report (Transit Cooperative Research Program), 71 Volume 5. Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/13841.
19. Sapronova Svitlana, Viktor Tkachenko, Oleksij Fomin, Viktoria Hatchenko, Sergiy Maliuk. 2017. „Research on the safety factor against derailment of railway vehicles”. *Eastern-European Journal of Enterprise Technologies* 6/7(90): 19-25. ISSN 1729-3774. DOI: https://doi.org/10.15587/17294061.2017.116194.
20. Shabana Ahmed A. 2012. „Nadal’s Formula and High Speed Rail Derailments”. *Journal of Computational and Nonlinear Dynamics* 7(4): 041003-041003-8.
21. Shabana Ahmed A., Zaazaa Khaled E., Sugiyama Hiroyuki. 2008. *Railroad Vehicle Dynamics: A Computational Approach.* Boca Raton: Taylor & Francis/CRC Press. ISBN 978-0-4290-9322-7. DOI: https://doi.org/10.1201/9781420045857.
22. Sperling E., Betzhold C. 1957. „Contribution to evaluation of comfortable running of railway vehicles”. *Bulletin of the International Railway Congress Association* 34: 672-678.
23. UIC Code 518 OR. 2003. *Testing and approval of railway vehicles from the point of view of their dynamic behaviour – Safety – Track fatigue – Ride quality. 2nd edition.* International Union of Railways.
24. Zeng Jing, Wei Lai, Wu Pingbo. 2016. „Safety evaluation for railway vehicles using an improved indirect measurement method of wheel-rail for ces”. *Journal of Modern Transportation.* 24(2): 114-123. DOI: https://doi.org/10.1007/s40534-016-0107-5.

Received 07.11.2019; accepted in revised form 16.01.2020