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SELECTED PROBLEMS IN RAILWAY VEHICLE DYNAMICS RELATED TO RUNNING SAFETY

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Abstract: *The paper includes a short review of selected problems in railway vehicle-track system dynamics which are related to the running safety. Different criteria used in assessment of the running safety are presented according to the standards which are in force in Europe and other countries. Investigations of relevant dynamic phenomena, including the mechanism of railway vehicle derailment, and the resulting modifications of the running safety criteria are also discussed.*

Key words: *railway vehicle, dynamics, running safety, derailment*

1. Introduction

Among the first problems that have emerged in the early development of the railways was guidance of the railway vehicle along the track and the associated excessive wear of wheel flanges. Solution to both problems was achieved in the second and third decades of the nineteenth century by the introduction of a conical wheel tread and a clearance between wheel flange and the rail head. This was primarily the result of empirical observations, supported by the intuition of the first constructors of railway vehicles, starting from George Stephenson who built the steam locomotive for the first public inter-city railway, the Liverpool and Manchester Railway [11]. Already then, the designers were aware that the introduction of wheels with conical profiles leads to the appearance of lateral vehicle vibrations (hunting) during the vehicle motion which are now known as kinematic oscillations.

Before it was possible to solve numerically the equations of motion of mechanical systems with many degrees of freedom with the aid of computers, investigations of the dynamics of railway vehicles were mainly done in a theoretical way and were focused on analytical relations associated with the running safety and the stability of the vehicle motion [52]. At this point one should mention the work by W. Klingel [30] on the wheelset hunting and the investigations of J. Nadal [35] aimed to determine the dynamic conditions in which there is a danger of derailment due to the wheel climb on the rail. The results of these studies, despite the passage of over a hundred years and a great development in the field of modeling of the railway vehicle-track systems and simulations of their motion, remain valid and are still used in the analysis of the dynamics of such systems.

2. Investigations of railway vehicle dynamics

The first realistic model of railway vehicle dynamics was proposed by Frederick W. Carter – a British engineer who graduated in mathematics at the University of Cambridge. In his model, he established that the forces acting between the wheels and the rails are proportional to the slip at the point of wheel-rail contact, which helped to explain the mechanism of the wheelset hunting within the theoretical description of the lateral motion of the vehicle. Further understanding the dynamics of railway vehicles, especially the stability of their motion, was significantly contributed to by the studies of Tadashi Matsuidara working at Railway Technical Research Institute of Japanese National Railways (JNR). The aim of these studies was to increase the vehicle speed and their results, indicating an important role of the vehicle suspension in ensuring the running safety, have been applied in the technical solutions used in the high-speed Shinkansen trains. Similar conclusions have been obtained a result of the investigations (largely independent of the Japanese studies) conducted by the group of A.H. Wickens at the research center of the British Railways in Derby since the early sixties of the last century. Another important, and, in fact, truly landmark step in the field of railway vehicle dynamics was the theory of rolling contact developed by J.J. Kalker [25] which has provided an effective way to determine tangential forces in the wheel-rail contact with high accuracy. A simplified form of this theory, known as the FASTSIM algorithm [24], is currently the most widely used method for determining contact forces in the simulation models of railway vehicle-track systems.

An important problem in the dynamics of railway vehicles is wheelset hunting which can strongly affect the running safety. Hunting is an undulating motion along the track, during which oscillatory changes of the lateral wheelset displacement from the track centre line are coupled with its yaw rotation which an oscillatory rotation of the wheelset around the axis perpendicular to the track plane. In the simplest terms wheelset hunting is purely kinematic phenomenon associated with the conicity of the wheels, whereas the wavelength of the hunting determined with the Klingel formula is independent of the railway vehicle velocity [30,41]. The phenomenon of the wheelset swaying motion while hunting along the track is very accurately described by W. Gąsowski and R. Lang [20]. To quote these authors, "swaying of a wheelset occurs when it moves without slip along the track direction, and some random factor, for example, local track irregularity knocks it out of the center position on the track, or deviates its axis from the direction perpendicular to the track" ([20]-(7)). As the authors point out in the summary of the work [20] the analysis of the hunting phenomenon extends the ability to understand manyphenomena associated with the dynamics of railway vehicles. An example of this approach is the works of the present author [26-28], which have analysed the impact of geometrical irregularities of the track on the wheelset hunting and the derailment coefficient which determines the running safety.

In general, the wheelset hunting is related to the stability of the railway vehicle motion and corresponds to oscillations with a fixed amplitude which occur at high vehicle velocities (above the critical speed). From a mathematical point of view, hunting is a kind of self-excited vibrations that after a long time become periodic vibrations called limit cycles. In linear models of railway vehicles–track systems such vibrations are represented by asymptotically unstable solutions of the equations of motion, which, according to the Routh-Hurwitz criterion, correspond to the roots of the characteristic equation with positive real parts. In the case of nonlinear models, studies based on the bifurcation theory have shown that, the Hopf bifurcation occurs in a railway vehicle-track system, which leads to the hunting of the wheelsets. At the same time, as it is underlined the author of the monograph [59], both sub-critical bifurcation, with a stable limit cycle (attractor) in a certain speed range, and supercritical bifurcation, with no stable periodic solution for any velocity, may occur in nonlinear models. Investigations of the wheelset hunting phenomenon and the stability of the railway vehicle motion using the bifurcation theory have been the subject of many works, among others [39,49,53,58,60].

The rapid development of the information technology and the increase in computing power of modern computers enables simulations of the dynamics of multibody systems (MBS) using increasingly accurate simulation models which describe them. The results of simulations of railway vehicle motion can be used to understand the basic phenomena which determine their dynamics [10,13,18,23]. Simulation studies are also a widely used approach for evaluating the dynamic properties of railway vehicles related to the running safety and the ride comfort [3,6,43]. Simulations are used at the stage of designing railway vehicles, in diagnosing problems occurring during vehicle operation, as well as in investigating the causes of railway accidents and their reconstruction. Simulations are used even to predict the dynamics of the vehicle after its derailment [2]. The use of simulations has many advantages compared to the experimental studies of the real systems: in addition to being much cheaper (by avoiding the cost of access to railway infrastructure), they provide possibility to perform tests in a much wider range of running conditions (even extreme ones which lead to the vehicle derailment) and allow one to determine quantities whose direct measurement is difficult or impossible (like creepages and forces present in the wheel-rail contact). Simulation models are also used for diagnosis and monitoring the state of the railway vehicle-track system [7,8].

In the studies of railway vehicle dynamics with the aid of simulations, though in many cases original programmes are still used to target specific problems, commercial software is increasingly more frequently applied, since it allows not only to carry out the simulations, but it also provides a convenient way to create a mathematical model using the graphical user interface and to automatically generate equations of motions. The first such program was MEDYNA developed by W. Kik [29]. A list of other currently available commercial packages includes ADAMS/Rail, NUCARS, SIMPACK Rail, VAMPIRE. Still, in many cases, due to the specific aspects of the examined problems and the possibility of full control over the applied simulation model and introduced modifications, original programmes are developed by the research groups working in the field of the railway vehicle dynamics. Examples of such are the programs developed at the Faculty of Transport of Warsaw University of Technology: ULYSSES package [5] used to automatically generate the equations of motion and the simulation programme [9] running in MATLAB.

3. Running safety of railway vehicle

3.1. Criterion of safety against derailment

Dynamic responses that are directly related to safety against derailment are forces in the contact zone between the railway vehicle and the track. Establishing this relationship was the result of the already mentioned studies by Nadal [35] who concluded that the derailment due to wheel climbing on the rail may occur when the ratio of the lateral (Y) and the vertical (Q) forces at the wheel-rail contact exceeds a certain limit value. This value depends on the flange angle related to the geometry of the contact and the coefficient of friction. The condition of safety against derailment based on the Nadal criterion but modified by accounting for the duration of the Y/Q impulse (or distance over which the actual derailment takes place) is an essential element in the evaluation of dynamic properties of railway vehicles and their approval for operation in accordance with the current regulations. These regulations include the EN 14363 standard [16], in force in the European Union, and the UIC 518 code [50] published by the International Union of Railways. The derailment criterion is also included in the technical standards used in the US [19,34] and Japan [47]. The determination of the derailment coefficient is also required in testing of railway vehicles by the regulation of the Polish Minister of Transport [40] in order to obtain certificates of admittance to operation for various types of railway vehicles, including locomotives, passenger cars, freight wagons as well as special and auxiliary vehicles.

The UIC 518 and EN 14363 standards include permissible length of the track section, on which the condition specified in the criterion Nadal can be violated without the risk of derailment. It should be noted, however, that despite the modifications taking into account, to a significant extent, the dynamic aspect of the derailment phenomenon, the Nadal criterion is based mainly on quasi-static conditions of the vehicle motion that lead to the risk of derailment by the wheel flange climb on the rail. However, the phenomenon of the wheel climb derailment is, in fact, dynamic in nature and it has been the subject of further intensive studies [1,3,4,8,14,15,18,21-23,31,33,36,37,42-44,46,54-58,61,62]. The goal of these studies is determination of the dynamic conditions leading to such type of derailment and developing new criteria for the assessment of the running safety. In particular, the investigations by Elkins and Wu [15,54,55] have revealed the need for such modifications of the derailment criterion that take into account the effect of the angle of attack (wheelset yaw angle). Also, one should mention a new approach to the derailment problem using the energy method [37,58].

The criterion for wheel climb derailment (criterion Nadal), specifies the maximum (limit) value of the ratio of the lateral force Y and the vertical force Q acting on the wheel at the point of wheel-rail contact. The ratio Y/Q is called the derailment coefficient. The limit value of this ratio depends on the wheel flange angle γ at the contact point and the coefficient of friction μ between the wheel and the rail. Since the derailment of the vehicle can occur if the value of this ratio exceeds the limit value for a sufficiently long period of time or track distance, the assessment of the safety against derailment following the mentioned standards is carried out by using the moving average $(Y/Q)_{2\mathrm{m}}$ calculated by averaging Y/Q over the window of the 2m width around each track point. According to the UIC 518 code and the EN 14363 standard the risk of derailment is high if $(Y/Q)_{2\mathrm{m}}$ exceeds $(Y/Q)_{\mathrm{lim}} = 0.8$. This limit value, adopted in these two standards, corresponds to $\mu = 0.6$ and the maximum value of the flange angle $\gamma = 70^{\circ}$ for the S1002/UIC60 wheel/rail profiles commonly used by the railways in the European countries. It should be noted that in the normal operation conditions the coefficient of friction μ is usually much lower, particularly on the side surface of the rail head (at the point of its contact with the wheel flange) where μ does not exceed 0.4 [45,46]. A typical value of $\mu = 0.36$ for the S1002/UIC60 wheel/rail profiles gives $(Y/Q)_{2\mathrm{m}} \le 1.2$. The latter condition is considered in the EN 14363 standard as the criterion for safety against derailment in quasi-static conditions corresponding to vehicle speeds below 40 km/h.

The occurrence of the risk of derailment depends strongly not only on the duration of the Y/Q impulse (i.e., large value of Y/Q in a short time interval), but also on the angle of attack ψ since exceeding the limit value by this ratio can lead to derailment only for large angles ψ. Namely, when the angle of attack does not exceed 5 mrad (approximately 3°) or becomes negative, the permitted values of Y/Q are much higher than it stems directly from the Nadal criterion [15,54,-56]. Such were the conclusions of derailment tests in running conditions conducted by the Association of American Railroads (AAR, USA) [45] and the results of simulation studies done with the NUCARS programme by the Transportation Technology Center Inc. (TTCI, USA) [56]. The following analytical form of the dependence of the limit value for the derailment coefficient on the angle of attack has been proposed by Elkins and Wu [15]:

$$\left(Y/Q\right)_{\lim} = \begin{cases} 1.0\,, & \psi > 5\,\mathrm{mrad} \\ 12/(\psi+7), & \psi < 5\,\mathrm{mrad} \end{cases} \qquad (1)$$

As a result of further investigations by TTCI more sophisticated analytical dependences on the angle of attack ψ have been developed for both the derailment coefficient and the derailment distance (i.e., the distance the vehicle runs until the wheel fully climbs on the rail) [54,55].

Another extension of the Nadal criterion, which defines the limit value $\left(Y/Q\right)_{\lim}$ for a single wheel (the one whose flange is in contact with the rail head), is the criterion proposed by H. Weinstock, which imposes a limit on the sum of the ratios Y/Q for the two wheels on the same axis [51]. Although the Weinstock criterion is known for almost 30 years and is considered [38,56] to be a more accurate and less conservative than the Nadal criterion, it is not included in the UIC 518 and EN14363 standards as the recommended method for assessing the running safety of railways vehicles.

Limit value of derailment coefficient and its dependence on derailment distance

As already noted above the time interval Δt or the length of a short track section Δx in which the ratio Y/Q must be exceed its limit value for the risk of derailment to occur, are included directly in the AAR [34] and Federal Railroad Administration (FRA) [19] standards which are in force in the United States. The AAR standard adopts the time interval $\Delta t = 0.05\,\mathrm{s}$ in accordance with the results of previous studies conducted by General Motors Electro-Motive Division (EMD) [31] and the Japanese National Railways (JNR) [33]. It was found in these studies that the limit value of Y/Q at which a railway vehicle can derail (as a result a wheel climbing on the rail) is much greater than the value determined from the Nadal criterion if the duration of an Y/Q impulse is shorter than 0.05 s. Furthermore, in the FRA standard [19] the value of the derailment distance $\Delta x = 5\,\mathrm{ft} = 1.52\,\mathrm{m}$ has been adopted for the limit value of Y/Q calculated directly with the Nadal formula for $\mu = 0.5$ and the flange angle γ corresponding to the pair of wheel/rail profiles that are actually used.

The derailment distance, i.e., the length Δx of the track section, in which the ratio Y/Q must exceed its limit value, is also accounted for in the UIC 518 code [50] and the European standard EN 14363 [16] which is in force in Poland. This is done in a indirect way, by using the moving average of Y/Q with the window of the width Δx. The above-mentioned results of the EMD [31] and JNR [33] investigations lead to the conclusion that the applied width Δx of the averaging window has a significant impact on the moving average $(Y/Q)_{\Delta x}$ and its limit value $(Y/Q)_{\lim}$ above which there is a risk of derailment. The window width $\Delta x = 2\,\mathrm{m}$ used to calculate the moving average $(Y/Q)_{\Delta x}$ of the derailment coefficient according to both the UIC 518 code and the EN 14363 standard is a fixed value corresponding to the limit value $(Y/Q)_{\lim} = 0.8$.

Dependence the moving average $(Y/Q)_{\Delta x}$ of the derailment coefficient on the window width Δx and the resulting necessity of modifying the limit value $(Y/Q)_{\lim}$ with the change of Δx has also been the subject of the research conducted by the present author [26]. This relationship has been analysed by determining the moving average $(Y/Q)_{\Delta x}$ for different window widths $\Delta x = 0.0, 0.4, 0.8, 2.0, 4.0\,\mathrm{m}$ ($\Delta x = 0.0$ means no averaging).

The mechanism of changing the 99.85 percentile value $(Y/Q)_{\Delta x}\big|_{0.9985}$ (used for direct comparison with $(Y/Q)_{\lim}$ according to the UIC 518 code and the EN 14363 standard) with the window width Δx is related to the fact that the application of the moving average leads to decreasing the magnitude of the local maxima of Y/Q. It has been found [26] that the obtained strong influence of the averaging window width Δx on the moving average $(Y/Q)_{\Delta x}$ and its percentile value $(Y/Q)_{\Delta x}\big|_{0.9985}$ is the consequence of the occurrence of short-lived Y/Q peaks during the vehicle motion along the track. These peaks occur as a result of wheelset hunting when the railway vehicle moves at a velocity greater than the critical speed so that bifurcation takes places and a limit cycle (corresponding to hunting) exists. During the hunting the wheel flange gets in contact the rail head in short time intervals when the wheelset is maximally displaced in the lateral direction. Such contact of the wheel flange with one of the rails, alternately for the left and right wheels, corresponds to the maximum value of the flange angle at the contact point which results in a large value of the ratio Y/Q (its local maximum) [17,20,22,26,27,28,41].

This explains why the percentile value $(Y/Q)_{\Delta x}\big|_{0.9985}$ determined for the window width Δx larger than the typical width (full width at half maximum) of local maxima of the function $(Y/Q)(x)$ (approximately 0.6 m - 1.0 m) is much smaller than the corresponding percentile value found for the raw (not averaged) signal $(Y/Q)(x)$ which is a direct result of measurements or simulations. This confirms that the limit value $(Y/Q)_{\lim}$ used for comparison with $(Y/Q)_{\Delta x}\big|_{0.9985}$ in assessment of the running safety has to be chosen in such way that it also depends on the applied window width Δx.

3.2. Criterion for lateral load of a rail vehicle on the track

Running safety is also related to lateral forces with which a railway vehicle acts on the track. The corresponding condition for this aspect of the running safety is the Prud'homme criterion that defines the limit value of the lateral load exerted by a railway vehicle on the track superstructure [48]. The lateral load of a wheelset on the track is given by the sum of the lateral forces present at the contact points of the left and right wheels with the rails, and the limit value of this sum depends on the vertical load exerted by the wheels on the track. The satisfaction of the Prud'homme criterion is one of the conditions required in tests of railway vehicle dynamics for their approval for operation in accordance with the UIC 518 code [50].

The Prud'homme criterion is applied to reduce the total lateral force exerted by a wheelset on the track in order to prevent the shift of the track panels in the ballast in the lateral direction as a result of the dynamic interactions occurring during the vehicle motion. Repeatedly exceeding the limit value of the lateral force acting on the track leads to a rapid though gradual increase of lateral shift of the track panels relative to the ballast. The result is a permanent deformation of the track which can become so large that there is a risk of derailment on the deformed section of the track, particularly in operation of high-speed trains. Limiting lateral load imposed by the Prud'homme criterion is particularly important in cases of noncontact tracks for which the phenomenon of the track buckling can take places due to the large longitudinal stresses (compressive) caused by increasing temperature.

Acceptable impact on the track superstructure depends on its resistance to permanent lateral deformation of the track (the track frame shift in ballast), and it is expressed by the limit value of the sum of the lateral forces acting on the track [48]. This relationship is given by the Prud'homme criterion [16,50] and it used to assess the running safety in the UIC 518 code.

The Prud'homme criterion has the following form:

$$\sum Y_{2\mathrm{m}} \le \alpha\left(10+\frac{P_0}{3}\right) \tag{2}$$

where: $\sum Y_{2\mathrm{m}}$ is the sum of the lateral contact forces acting on the wheelset (at the points of contact of the two wheels with rails) averaged around each track point over the 2 m wide window (similarly as it is done for the derailment coefficient), expressed in kN, P_0 is the value of the vertical axle load expressed in kN and α is the coefficient depending on the type of railway vehicle and it is equal to $\alpha = 1$ for a passenger car.

According to the UIC 518 code the quantity $\sum Y_{2\mathrm{m}}$ used in the above criterion is the maximum value of the module $\sum Y_{2\mathrm{m}}$, after rejecting 0.15% and 0.15% of maximum and minimum values $\sum Y_{2\mathrm{m}}$ obtained from measurements or determined in simulations.

3.3. Maximum values of railway vehicle body accelerations

Another condition for the running safety included in the UIC 518 code for application for a passenger car moving along a tangent track sets the limits for the maximum values of the vehicle body acceleration in the lateral direction $\left(\left|\ddot{y}\right|_{\max}\right)_{\lim} = 2.5\,\mathrm{m/s^2}$ and the vertical direction (for a two-stage suspension): $\left(\left|\ddot{z}\right|_{\max}\right)_{\lim} = 2.5\,\mathrm{m/s^2}$.

An additional criterion contained in the UIC 518 code, which is not directly related to the running safety, but determines the required operating conditions is defined by imposing the limits on the rms values of the body accelerations, i.e., their standard deviations (since their mean values vanish in the case of the vehicle motion along a tangent track). The limit values of the standard deviations of the vehicle body acceleration are: $\left(\sigma_{\ddot{y}}\right)_{\lim} = 0.5\,\mathrm{m/s^2}$ for the lateral direction and $\left(\sigma_{\ddot{z}}\right)_{\lim} = 0.75\,\mathrm{m/s^2}$ for the vertical direction (in a railway vehicle with two-stage suspension).

4. Summary

The running safety is one of main topics in studies of the railway vehicle dynamics. Ensuring the ultimate level of the running safety and, in particular, preventing derailments of railway vehicles is in fact the fundamental requirement in operation of the rolling stock. This requirement is expressed in a quantitative way through the criteria that are contained in the national and international regulations regarding testing and approval of railway vehicles. The subject of these criteria are the forces which act at the wheel-rail contact points and the limit values that are imposed on the derailment coefficient and the lateral load on the track which are both expressed in terms of these forces. Vehicle body accelerations are also the subject of limiting their maximum values which is another criterion whose satisfaction is required to ensure the running safety. However, none of these criteria alone fully determines the conditions in which the running safety is compromised and, in particular, the risk of derailment is increased. Therefore, the simultaneous use of multiple criteria in assessment of the running safety is fully justified and improvement of these criteria is still a subject of numerous studies and publications regarding the dynamics of railway vehicles and the running safety.

References

[1] Barbosa, R.S.: A 3D contact safety criterion for flange climb derailment of a railway wheel. Vehicle System Dynamics 42 (5), 2004, pp. 289–300.

[2] Boronenko Yu., Orlova A., Iofan A., Galperin S.: Effects that appear during the derailment of one wheelset in the freight wagon: simulation and testing, Vehicle System Dynamics, vol. 44, Supplement, 2006, pp.663–668.

[3] Brabie D., Andersson E.: Dynamic simulation of derailments and its

consequences, Vehicle System Dynamics, vol. 44 supplement, 2006, pp. 652–662.

[4] Chelli F.et all: Effect of track geometrical defects on running safety of tramcar vehicles, Vehicle System Dynamics, vol. 44 supplement, 2006, pp. 302-312.

[5] Choromański W.: The software package ULYSSES for automatically generations of equations and simulation of railway vehicle motion, Konf. Transport System Engineering, Politechnika Warszawska 1995.

[6] Choromański W., Zboiński K.: Synthesis of control to improve lateral dynamics of railway vehicles, Proceedings of the 13th IAVSD Symposium on the Dynamics of Vehicles on Roads and on Tracks, Sichuan (China). Vehicle System Dynamics 23 n Suppl., 1994, pp. 47-58.

[7] Chudzikiewicz A., Elementy diagnostyki pojazdów szynowych, Wyd. Inst. Technologii Eksploatacji, Biblioteka Problemów Eksploatacji, Radom 2002.

[8] Chudzikiewicz A.: Monitorowanie stanu układu dynamicznego pojazd szynowy-tor, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2012.

[9] Chudzikiewicz A., Droździel J., Sowiński B.: Wykorzystanie MATLAB-a do symulacji dynamiki pojazdu szynowego, II Warsztaty Naukowe "Symulacja w Badaniach i Rozwoju", PTSK IPPT PAN, Materiały Konf., Warszawa, listopad 1995, (pp.51-53).

[10] Clark R. A., Eickhoff B. M., Hunt G. A.: Prediction of the dynamic response of vehicles to lateral track irregularities, Proceedings of 7th IAVSD Symposium 1981, pp.535-548.

[11] Dendy Marshall C.F.: A history of British railways down to the year 1830, London: Oxford University Press. 1938, pp.147-148.

[12] Droździel J., Kardas-Cinal E., Sowiński B.: Railway vehicle safety assessment affected by wheel and rail wear, Proceedings of the 11th Mini Conference on “Vehicle System Dynamics, Identification and Anomalies”, VSDIA 2010, Budapest, Hungary 8-10 November, 2010, pp. 81-88.

[13] Droździel J., Sowiński B., Railway car dynamic response to track transition curve and single standard turnout. Computers in Railways X, WIT Press 2006 - Southampton, Boston.ISBN: 1-84564-177-9, pp. 849-858.

[14] Droździel J., Kardas-Cinal E., Sowiński B., Railway vehicle safety assessment affected by wheel and rail wear. VSDIA 2010 – 12th International Conference onVehicle System Dynamics, Identification and Anomalies, Budapest, 8-10 Nov. 2010, pp. 81-88

[15] Elkins J., Wu H.: New criteria for flange climb derailment, Railroad Conference, 2000. Proceedings of the 2000 ASME/IEEE Joint Volume , 1-7, 2000.

[16] EN 14363: Railway applications - Testing for the acceptance of running characteristics of railway vehicles - Testing of running behaviour and stationary tests. European Committee For Standardization, 2005.

[17] Esveld K.C.: Modern railway track, MRT - Productions, Duisburg 1989.

[18] Evans J., Berg M.: Challenges in simulation of rail vehicle dynamics, Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, Volume 47, issue 8, 2009, pp. 1023 – 1048.

[19] Federal Railroad Administration, Track Safety Standards, Part 213, Subpart G, September 1998.

[20] Gąsowski W., Lang R.: Kołysanie poprzeczne zestawu kołowego podczas wężykowania w torze(1-7), Pojazdy Szynowe: nr 2, s. 35-44,1999 (1), nr 3, s. 26-49, 1999 (2), nr 4, s. 1-18, 1999 (3), nr 1, s. 1-26, 2000 (4), nr 2, s. 1-8, 2000 (5), nr 4, s. 1-7, 2000 (6), 2001, nr 2, s. 1-9, 2000 (7).

[21] Hung C., Suda Y., Aki M.,Tsuji T., Morikawa, M., Yamashita T., Kawanabe T., Kunimi T.: Study on detection of the early signs of derailment for railway vehicles, Vehicle System Dynamics; supplement, 2010, vol. 48, pp. 451-466,

[22] Iwnicki S. (ed.): Handbook of railway vehicle dynamics, CRC Press Inc., 2006.

[23] Jun X., Qingyuan Z.: A study on mechanical mechanism of train derailment and preventive measures for derailment, Vehicle System Dynamics, vol. 43, No. 2, February 2005, pp.121 – 147

[24] Kalker J.J.: A fast algorithm for the simplified theory of rolling contact, Vehicle System Dynamics 11, pp.1- 3, 1982.

[25] Kalker, J. J.: On the rolling contact of two elastic bodies in the presence of dry friction, Doctoral Thesis, Delft, 1967.

[26] Kardas-Cinal E.: Bezpieczeństwo i komfort jazdy pojazdu szynowego z uwzględnieniem losowych nierówności geometrycznych toru, Prace Naukowe „Transport" z. 94, Oficyna Wydawnicza Politechniki Warszawskiej Warszawa, 2013

[27] Kardas-Cinal E.: Spectral analysis of derailment coefficient in railway vehicle - track system with random track irregularities, artykuł - 8 stron (wersja elektroniczna na CD): Proceedings of 21st International Symposium on Dynamics of Vehicles on Roads and Tracks. IAVSD´09, 17-21 August 2009, KTH, Stockholm, Sweden; abstract: Abstract Book IAVSD"09, pp. 360-361.

[28] Kardas-Cinal E.: Spectral distribution of derailment coefficient in non-linear model of railway vehicle – track system with random track irregularities, Journal of Computational and Nonlinear Dynamics (ASME) 8, 2013, 031014 (9 pages).

[29] Kik W.: MEDYNA, User Manual, ArgeCare 1997

[30] Klingel W.: Über den Lauf von Eisenbahnwagen auf Gerarder Bahn. Organ fűr die Fortschritte des Eisenbahnwesens, 20, 113-123, 1883.

[31] Koci H.H. and Swenson C.A., Locomotive wheel-loading – a system approach, General Motors Electromotive Division, LaGrange, IL, February, 1978.

[32] Matej J.: Modelowanie oraz symulacyjne badania wagonów bimodalnych w kategorii zagrożenia wykolejeniem, Oficyna Wydawnicza PW 2010, Zeszyt "Mechanika" nr 234, ISSN: 0137-2335

[33] Matsudaira T.: Dynamics of high speed rolling stock, Japanese National Railways RTRI Quaterly Reports, Special Issue, 1963.

[34] M1001, AAR Mechanical Division, Manual of standards and recommended practices, section C – Part II, Volume 1, Chapter XI, Section 11. 5.2 Track- Worthiness Criteria, Adopted 1987, Revised 1993.

[35] Nadal M. J.: Theorie de la stabilite des locomotives, Part 2, Movement de Lacet, Annales des Mines, vol. 10, 1896, str. 232.

[36] Nagase K.,Wakabayashi Y., Sakahara H.: A study of the phenomenon of wheel climb derailment: results of basic experiments using model bogies, Proc. Instn. Mech. Engrs., vol 216 Part F: J Rail and Rapid Transit, 2002 ,pp. 237-247.

[37] Opala M.: Analysis of experimental data in the context of safety against derailment of a railway vehicle, using the energy method, Key Engineering Materials, vol. 518, 2012, pp.16-23.

[38] Piotrowski J.: Poprzeczne oddziaływanie między pojazdem i torem– podstawy modelowania numerycznego, Prace Naukowe PW, seria Mechanika Z.118, 1990.

[39] Polach O., Kaiser I.: Comparison of methods analyzing bifurcation and hunting of complex rail vehicle models, J. Comput. Nonlinear Dynam. 7, 2012, 041005 (8 pages).

[40] Rozporządzenie Ministra transportu, budownictwa i gospodarki morskiej z dnia 7 sierpnia 2012 r. w sprawie zakresu badań koniecznych do uzyskania świadectwa dopuszczenia do eksploatacji typu budowli przeznaczonej do prowadzenia ruchu kolejowego, świadectwa dopuszczenia do eksploatacji typu urządzenia przeznaczonego do prowadzenia ruchu kolejowego oraz świadectwa dopuszczenia do eksploatacji typu pojazdu kolejowego. Dziennik Ustaw, Poz. 918, 2012.

[41] Shabana A.A., Zaazaa, K.E., Sugiyama, H.: Railroad vehicle dynamics: a computational approach, Taylor & Francis/CRC, 2008.

[42] Shabana A.A.: Nadal's formula and high speed rail derailments, J. Comput. Nonlinear Dynam. 7, 2012, 041003 (8 pages).

[43] Shu X., Wilson N.: Simulation of dynamic gauge widening and rail roll: effects on derailment and rolling contact fatigue, Vehicle System Dynamics, vol. 46, supplement, 2008, pp. 981–994.

[44] Shu X., Wilson N., Wu H., Tunna J.: A bi-parameter distance criterion for flange climb derailment, Rail Conference, 2005. Proceedings of the 2005 ASME/IEEE Joint.

[45] Shust W., Elkins J., Kalay S., El-Sibaie: Flange climb derailment tests using AAR's Track Loading Vehicle, Research Report R-

910, Association of American Railroads, December 1997.

[46] Sobaś M.: Stan i doskonalenie kryteriów bezpieczeństwa przed wykolejeniem pojazdów szynowych (1), Pojazdy Szynowe nr 4, 2005, str. 1-13, (część 2), Pojazdy Szynowe nr 2, 2006, str. 37-48.

[47] Technical Standard for Japanese Railway, available at http://www.mlit.go.jp/english/2006/h_railway_bureau/Laws_concerning/index.html

[48] Towpik K.: Linie kolejowe dużych prędkości, Problemy Kolejnictwa – Zeszyt 151,2010, str. 28-70.

[49] True H., Jensen J.C.: Parameter study of hunting and chaos in railway vehicle dynamics. Lugner, Peter; Hedrick, J. Karl (Eds.): Vehicle System Dynamics. Proc. of 13th IAVSD Symposium August 23-27, 1994, Chengdu, Sichuan, China. Swets and Zeitlinger ,1994, 508-520.

[50] UIC Code 518 OR: Testing and approval of railway vehicles from the point of view of their dynamic behaviour - Safety – Track fatigue-Ride quality, International Union of Railways, 2nd ed., April 2003.

[51] Weinstock H.: Wheel climb derailment criteria for evaluation of rail vehicle safety, Paper no. 84-WA/RT-1, 1984 ASME Winter Annual Meeting, New Orleans, LA, November 1984.

[52] Wickens A.: A history of railway vehicle dynamics, in [22], pp. 5-38.

[53] Wickens A.: Steering and dynamic stability of railway vehicles, Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, volume 5, issue 1-2, 1976, pp.15-46.

[54] Wu, H., and J. Elkins, Investigation of Wheel Flange Climb Derailment Criteria, Report R-931, Association of American Railroads, Washington, D.C., July 1999.

[55] Wu H., Shu X., Wilson N.: TCRP Report 71, Track-Related Research, Volume 5: Flange Climb Derailment Criteria and Wheel/Rail Profile Management and Maintenance Guidelines for Transit Operations, Transportation Research Board of the National Academies (USA), 2005.

[56] Wu H., Wilson N.: Railway Vehicle Derailment and Prevention, in [22], pp. 209-237.

[57] Xinbiao Xiao, Xuesong Jin,Yongquan Deng and Zhongrong Zhou, Effect of curved track support failure on vehicle derailment, Vehicle System Dynamics, Vol. 46, No. 11, November 2008, pp.1029–1059.

[58] Xiang .J, Zeng Q. Y.: Mechanism and energy random analysis of train derailment on railway bridges, International Journal of Structural Stability and Dynamics, vol. 9, No. 4, 2009, pp. 585-605.

[59] Zboiński K., Metodyka modelowania dynamiki pojazdów szynowych z uwzględnieniem zadanego ruchu unoszenia i jej zastosowania. Prace Naukowe Transport z. 43. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2000

[60] Zboiński, K., Dusza, M.: Self-exciting vibrations and Hopf's bifurcation in non-linear stability analysis of rail vehicles in curved track. European Journal of Mechanics, Part A/Solids, vol. 29, no. 2, 2010. pp.190-203.

[61] Zeng Jing , Guan Qinghua, Study on flange climb derailment criteria of a railway wheelset, Vehicle System Dynamics, Vol. 46, No.3, March 2008, pp. 239–251

[62] Zeng J., Wu P.: Study on the wheel/rail interaction and derailment safety. Wear vol. 265, 2008, pp. 1452–1459.