

ON THE METHOD OF DETERMINING SAFETY CRITERIA AGAINST ROLLING STOCK DERAILMENT

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Abstract: *The international regulations used to assess the dynamic behaviour of railway vehicles – UIC code 518 and EN 14363 – define a set of testing conditions. Under these regulations, the so-called normal method of assessing the movement safety is based on the measurement of forces Y_1 (horizontal-crosswise) and Q_1 (vertical) of the attacking wheel-rail contact. The so-called “nominal criterion” with participation of a horizontal nominal force called “frame” or “axial” is introduced as an initial (given) real criterion. The “frame”/“axial” force is transmitted between the axle and frame and the vertical force representing the resultant force at the contact point of attacking wheel. The vertical load on the two wheels of a wheel-axle and the geometric position of nominal force are taken into consideration. The introduction of Q_2/Q_1 as a diagnostic parameter in the system leads to improvement.*

Key words: *Railway vehicles, rolling stock, derailment, safety criteria against derailment.*

1. INTRODUCTION

Rail transport is a complex "technological" system operating under the conditions and influence of a number of technical, social, economic and even political factors.

To achieve a quality transport service, it is required to apply an integrated approach to the nature, specificities and interconnection of individual (partial) issues of reliability and safety into the respective rail transport system. The main aspect in this direction is the establishment and maintenance of a system for reliability and safety management. It is a regulatory management system with a characteristic structure (defined by the objectives, tasks, directions and strategy to solve the problems of operational reliability and safety) defining standards and procedures for safe functioning of the individual railway subsystems [1].

In general, four groups of factors influencing on risk occurrence in the transport activity and a transport accident respectively can be defined:

- Technical factors – all technical faults of vehicles, infrastructure [2, 3, 4] and special equipment.
- Subjective factors – caused by the railway vehicle drivers or organizers of transport processes.
- Organizational (technological) factors – imperfections of technology, organization and management of the transport process.
- Other factors – influence of "operational environment" (atmospheric conditions, interaction with other types of transport systems, etc.).

The technical operation and safety in rail transport are not time-consistent concepts [5, 6]. The operational environment can be changed in a very short time and offer unknown conditions for the transport process implementation such as an emergency situation with hazards that have been unidentified until present. To avoid such situations, operational staff needs to apply adequate professional actions. People working in rail operation systems must be well trained and possess sufficient knowledge in all aspects of safety (nature, influencing factors, potentially possible hazards in the workplace, way of action in unusual and emergency situations, restorative actions after accidents, etc.).

The classical rolling stock derailment occurs as flange climbing onto the rail head [7, 8] or the track gauge extension. As far as derailments consist a significant part of the total number of accidents, the study on this phenomenon by the methods of probability theory and mathematical statistics is of considerable scientific interest.

The railway accident “derailment” can be classified into six main types [7, 8]:

- classical derailment;
- collision of rolling stock with fixed obstacles and people;
- loss of strength and durability of the elements of superstructure, wheeled part and vehicle structure;
- failure in the rail transport management technology;

- other cases such as expansion of track gauge due to high temperatures, disasters, etc.;
- faults in signalling and power supply systems.

The subtypes of each main type of derailment are as follows:

(a) in the case of classical derailment:

- derailment when the flange climbs onto the rail head;
- derailment when the track gauge is widened .

(b) in the case of a collision between rolling stock and fixed objects and people:

- with hitting running rolling stock;
- with shunting;
- with hitting a fixed barrier (including large-gauge and small-gauge objects, elements of switches and intersections);
- with hitting people.

(c) in the case of strength and durability loss:

- derailment due to broken rails and elements of switches and crossings under a running vehicle;
- derailment due to broken elements of wheeled parts (wheels, axles, wheelsets, spring suspension and coupling elements);
- derailment due to train breaking while running (draw gear, central bolted beams, body-bogie link, etc.).

(d) due to failures of technology and management:

- failure in the mechanism of transport process management (reception of the train on an occupied track; directing the train to a busy section, accepting and directing the train to an unprepared route; running at a prohibitive signal);
- failure of the shunting management mechanism;
- failure of the control mechanism of loading and unloading operations and strengthening of load (loss of load, disbalancing of load, etc.).

(e) derailment due to track temperature expansion, disasters, etc.:

- derailment due to track expansion because of high temperatures;
- twisting of rails due to absence of ballistic prism or other elements;
- unacceptable wear-out of rail head and joints, etc.

(f) failures in signalling systems and electricity supply:

- derailments due to failures of automation devices;
- derailments due to failures of telemechanics;
- derailments due to failures of power supply devices.

The incidents and accidents in railway transport caused by rolling stock derailments have always consisted the highest share of all railway accidents everywhere in the world – in all cases being over 50% and reaching even up to 80-90% [9]. It is not occasional that the derailment is considered a typical (even the most popular) rail rolling stock incident.

The experience, research and contributions of Bulgaria, especially of the Research Institute of Transport with Bulgarian Railways (BDZ), to avoid or reduce the accidents due to rail rolling stock derailment have been related mostly to operating speeds up to the permissible maximum + 10%.

The cases of derailment under these conditions (at operating speeds) are much rarer than those at low speeds and that obviously gives reasons to many professionals to consider that running at low speeds is dangerous from the viewpoint of "derailments". That is indisputably true if in "comparison" the number of accidents is considered more decisive than material damage and human casualties. Obviously, without any further details, it could be concluded that the derailment at operating speeds is not less significant than those occurring at lower speeds.

2. INTERNATIONAL REGULATIONS AND STANDARDS FOR DETERMINATION OF SAFETY CRITERIA AGAINST DERAILMENT.

Under Directive 2004/49/EC [10] each EU member state shall ensure that it provides railway safety and increase of its level in compliance with the development of Community legislation and scientific and technical progress. For this purpose, European Railway Agency (ERA) was established [9]. To address the assigned tasks, Common Safety Methods (CSM) [11] have been developed to increase the level of rail transport safety and harmonize safety requirements in all EU countries [12]. The "Railway Administration" Executive Agency (RAEA) is the national safety authority in railway transport of the Republic of Bulgaria [13]. In 2006 the Ministry of Transport and Communications established a specialized unit for investigation of accidents and incidents in railway transport (SUIAIRT) as part of the ministry structure [14]. A number of methods and sensory systems have been developed to measure the forces of wheel-rail interaction under operational conditions [15-22].

The dynamic parameters that are directly related to safety against derailment include the forces in contact area between the railway vehicle and track. The establishment of this relationship is a result of Nadal's studies [23], which have shown that derailment might occur when the ratio of lateral (Y) and vertical (Q) forces in wheel-rail contact exceeds a certain boundary value. This value depends on the angle of flange, the geometry of contact and the coefficient of friction.

The state of safety against derailment based on criterion “Nadal” but modified by taking into account Y/Q pulse duration (or the distance, which actual derailment takes place within) is an essential element of assessment of rolling stock dynamic properties and their approval for operation according the provisions in force.

These regulations include EN 14363 standard [24] valid in the European Union and UIC 518 [25] published by the International Union of Railways. The derailment criterion is included also in the technical standards used in the US [26] and Japan [27].

The UIC 518 and EN 14363 standards include the permissible length of track section where the condition in Nadal criterion can be violated without a risk of derailment. However, it should be noted that despite the modifications, which considerably take into account the dynamic aspect of derailment phenomenon, Nadal criterion is based predominantly on quasi-static conditions of a running vehicle that lead to risk of derailment due to flange climbing on the rail. However, the derailment phenomenon with wheel climbing is in fact dynamic in nature and a subject of further intensive examinations.

The purpose of these studies is to determine the dynamic conditions leading to this type of derailment and develop new criteria to assess safety with movement. In particular, the studies made by Elkins and Wu [28, 29, 30] have revealed the need of such modifications of derailment criterion, which take into account the effect of angle of attack. It is also worth mentioning the new approach to derailment problem using the energy method [22, 31].

Nadal derailment criterion determines the maximum (limited) value of ratio between lateral force Y and vertical force Q acting on the wheel at the point of wheel-rail contact. Since a vehicle derailment might occur if the value of this ratio exceeds the limit of admissible value for a sufficiently long period of time or a distance of track, the derailment safety assessment following these standards shall be performed using an average value $(Y/Q)_{2m}$ calculated by averaging Y/Q ratio in a window width of $2m$ around each route point. According to UIC 518 and EN 14363, the risk of derailment is high if $(Y/Q) > (Y/Q)_{lim} = 0,8$. This boundary value adopted in these two standards corresponds to the coefficient of “wheel-rail” friction $\mu = 0,6$, and to the maximum value of wheel angle $\gamma = 70^\circ$ in profiles of wheels and rails respectively – S1002/UIC60, which are used in the European countries. It should be noted that under normal operating conditions the friction coefficient μ is usually much lower, especially on the rail head lateral surface (at the point of contact “wheel-flange”) [32, 33]. For the assumed value – $\mu = 0,36$ of wheel/rail profiles S1002/UIC60, the ratio is assumed $(Y/Q)_{2m} \leq 1,2$. The latter condition is examined in EN 14363 standard as a criterion of safety against derailment under quasi-static conditions corresponding to vehicle speeds less than 40 km/h .

The occurrence of derailment risk strongly depends not only on the pulse duration Y/Q (i.e. a high value of Y/Q in a short time interval), but also on the angle of attack of the attacking wheel – α , since exceeding the limit value of this ratio can result in derailment only at large angles of attack. When the angle of attack does not exceed 5 mrad (approximately 3°) or becomes negative, the Y/Q limit values are much higher than those obtained directly by Nadal criterion [23, 28, 29, 30]. Such conclusions have been drawn from a derailment test with running conducted by the Association of American Railways (AAR, USA) [32] and such results have been obtained by the simulation studies carried out with the NUCARS programme of the Transport Technology Centre (TTCI, USA) [29,30]. The limit value of the derailment coefficient proposed by Elkins and Wu [28] is $(Y/Q)_{2m} = 1,0$ for attack angles $\alpha > 5 \text{ mrad}$ and $(Y/Q)_{2m} = 12/(\alpha + 7)$ for angles $\alpha < 5 \text{ mrad}$.

The criterion proposed by H. Weinstock imposed a limit on the sum of ratios Y/Q for both wheels on the same axle [34]. This criterion is not included in UIC 518 and EN14363 standards as a recommended method of assessing the current safety of railway vehicles.

The international regulations (standards) for testing used to assess the dynamic behaviour of railway vehicles – UIC code 518 and EN 14363 define a set of test conditions, describe the data processing rules and give the limit values of specified quantities of assessment.

The regulations mentioned above state that the so-called normal method is based on the measurement of the contact forces Y (horizontal-transverse) and Q (vertical) of wheel/rail contact [35] indicating the following evaluation parameters:

- ΣY , the total force exercised laterally on the track by wheel axles;
- Y/Q ratio used to assess the risk of derailment by flange climbing onto rail head;
- Y_{qst} , the mean value of the lateral distortion force exercised on the outer rail in curves;
- Q , the maximum vertical force exercised on the outer rail in curves;
- Q_{qst} , the mean value of vertical force exercised on the outer rail in curves.

The first two forces (ΣY and Y/Q) are considered important for safety while the others are used to assess the track fatigue.

In addition, the lateral accelerations are measured on the bogie frame (above the wheel axles) and the lateral and vertical accelerations are measured in the body (above the central bearings). The body accelerations are used in the normal method for evaluating the “running behaviour”.

Other alternative methods defined as “simplified” are described in UIC 518 and EN 14363. These methods are based mostly on these accelerations (bogie frame and body). However, although one and the same methods can be applied to accelerations, this document focuses only on the factors of influence of wheel/rail forces assessed within the normal method as safety and track fatigue criteria.

For the "maximum" quantities of measurement (ΣY , Y/Q and Q) the value of 99.85%, which is the absolute one, and/or 0.15% of the negative signal are selected.

For the whole test area, when the statistical process used is one-dimensional, the maximum estimate is defined as "mean ± 3 standard deviations" of N individual values.

For quasi-static values (Y_{qst} and Q_{qst}), the used quantity is 50% of the filtered signal value for each section of the track while the estimated value in the test area is determined as average of these N individual values.

The limit values for evaluation of safety and fatigue track (axle load $\leq 22,5 t$) are as follows:

$$(\Sigma Y)_{lim} = (10 + P_0/3) kN, \text{ where } P_0 \text{ is the static load of axles in } kN \quad (1)$$

$$(Y/Q)_{lim} = 0,8 \quad (2)$$

$$(Y_{qst})_{lim} = 60 kN \quad (3)$$

(в UIC 518: 2009: $30 + 10500/Rm$, where Rm is the mean radius of the sections used)

$$(Q_{qst})_{lim} = 145 kN \quad (4)$$

$$(Q)_{lim} = (90 + Q_0) kN \quad (5)$$

with limitation according to the high speed where Q_0 is the static load of wheel.

3. EXPERIMENTAL DETERMINATION OF THE SAFETY CRITERION AGAINST DERAILMENT

The experimental determination of safety criterion against derailment under quasi-static conditions is carried out either by direct measurement of forces Y_1 and Q_1 or by direct measurement with computation of the same forces.

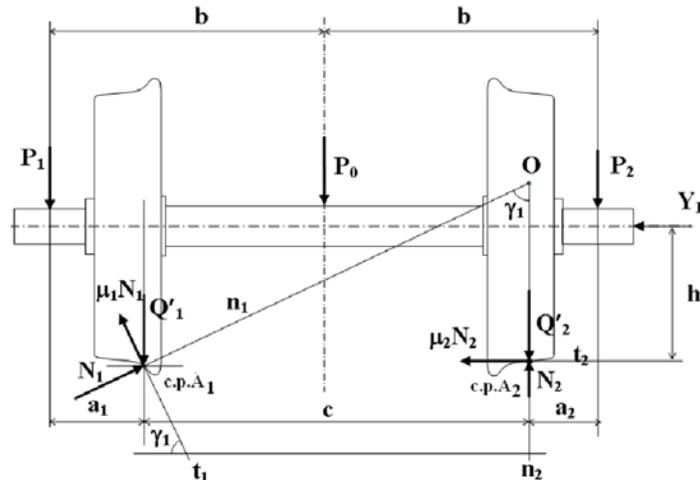


Figure1. Computational scheme for determining the so-called “Nominal” criterion against derailment

The computational scheme of the task is given in Fig. 1 where the attacking wheel I contacts the rail edge rounded by the flange with point A_1 in the conical zone (or if there is not such one, in the inflection zone) where the slope angle γ_1 to the horizontal has a maximum value and the non-attacking wheel contacts point A_2 of the rolling surface to the upper surface of the rail head; due to the small slope of rolling surface at contact point A_2 ($\gamma_2 < 2^\circ$), in these examinations it will be accepted as zero ($\gamma_2 = 0^\circ$). Vertical forces P_1 and P_2 transmitted from the structure are applied to the axle necks of wheels 1 and 2 respectively, and force P_0 of the wheel axle own weight is applied to its centre; horizontal force Y_p transmitted by the structure to the wheel axle known as "frame force" is applied at a distance h in vertical direction from the horizontal plane of rail heads, whereby this distance is assumed to be not only equal, but also less or greater than the radii of wheels. Reactive forces N_1 and N_2 at contact points A_1 and A_2 respectively follow the directions of respective normals n_1 and n_2 to the supporting surfaces and friction forces $\mu_1 N_1$ и $\mu_2 N_2$ have the same directions as respective tangents t_1 and t_2 and opposite directions of the preset displacements.

To solve the system described above, the principle of virtual displacements in analytic mechanics is applies.

As an initial (given) real criterion that should be adapted to ratio Y/Q approved internationally according to EN 14363 and UIC 518, the so-called "nominal" criterion Y_p/Q_1 with participation of horizontal nominal force Y_p called "frame" or "axial" transmitted between the axle and frame is introduced [39, 40]; as well as vertical force Q_1 representing the resultant force at the contact point of attacking wheel:

$$\frac{Y_p}{Q'_1} = \frac{1 - \frac{\mu_1}{\sin \gamma_1 (\cos \gamma_1 + \mu_1 \sin \gamma_1)} - \frac{Q'_2}{Q'_1} \cdot \frac{\mu_2}{\operatorname{tg} \gamma_1}}{\cot \gamma_1 - \frac{h}{c} + \frac{\mu_1 \cdot h / c}{\sin \gamma_1 (\cos \gamma_1 + \mu_1 \sin \gamma_1)} - \frac{\mu_2 \cdot h / c}{\operatorname{tg} \gamma_1}} \quad (6)$$

where: γ_1 and μ_1 – the angle of flange and friction coefficient at the flange-rail contact point of attacking wheel respectively; μ_2 – friction coefficient at the flange-rail contact point of non-attacking wheel; Q'_2 and Q'_1 – vertical load on both wheels of a wheel-axle and h/c – parameter taking into account the geometry location of nominal force Y_p .

The internationally validated criterion of Nadal $Y/Q = Y_1/Q_1$ is:

$$\frac{Y}{Q} = \frac{Y_1}{Q_1} = \frac{\operatorname{tg} \gamma_1 - \mu_1}{1 + \mu_1 \cdot \operatorname{tg} \gamma_1} \quad (7)$$

and with the correction made by Marie G.

$$\frac{Y}{Q} = \frac{Y_1}{Q_1} = \frac{\operatorname{tg} \gamma_1 - \mu_1}{1 + \mu_1 \cdot \operatorname{tg} \gamma_1} - \frac{Q'_2}{Q'_1} \cdot \mu_2 \quad (8)$$

is temporarily replaced by the so-called "conditional transforming" criterion against derailment Y_1/Q_1 , which is closer to reality, being characterized by factually acting adapted (reduced) forces Y_1 and Q_1 at the contact point of attacking wheel. It helps to achieve methodological compatibility with the initial criterion assumed temporarily with deviation $Y_1/Q_1 \approx Y/Q$ acceptable in practice.

The determination of Y/Q criterion validated by the Euro-norms and UIC criterion is possible only experimentally, at that with the help of a special force-measuring wheel axle with appropriate equipment and staff provided by the owner to be used under certain conditions; or giving tests to be completely performed by West European companies, which is even more disadvantageous for Bulgaria. This state inevitably generates an alternative to seek another solution at least for the most common cases of low responsibility – for example, according to the objective set here – the theoretical determination of criterion against derailment Y_1/Q_1 and Y/Q respectively, by no direct method but indirectly as follows: by theoretical or experimental determination of the nominal criterion against derailment Y_p/Q'_1 and its subsequent adaptation to conditional criterion Y_1/Q_1 , which is considered equivalent to criterion Y/Q established in compliance with EN and UIC. As for the actual adaptation from Y_p/Q'_1 to Y_1/Q_1 , it is based on the disclosed methodological compatibility and the transformational dependencies between criteria Y_p/Q'_1 and Y_1/Q_1 :

$$\frac{Y_1}{Q_1} = \frac{Y_p / Q'_1}{1 + Y_p / Q'_1 \cdot h / c} \left[1 - \mu_2 \cdot \frac{h}{c} \left(1 + \frac{Q'_2}{Q'_1} \right) \right] \quad (9)$$

Fig. 2 shows the dependency between criteria Y_1/Q_1 and Y_p/Q'_1 with different values of $\mu_1 (= 0,3; 0,36; 0,4)$, with different values of ratio $Q'_2/Q'_1 (= 0; 0,5; 1; 1,5; 2)$ for wagon axles of $\phi 920\text{mm}$, which are standard ones according to UIC.

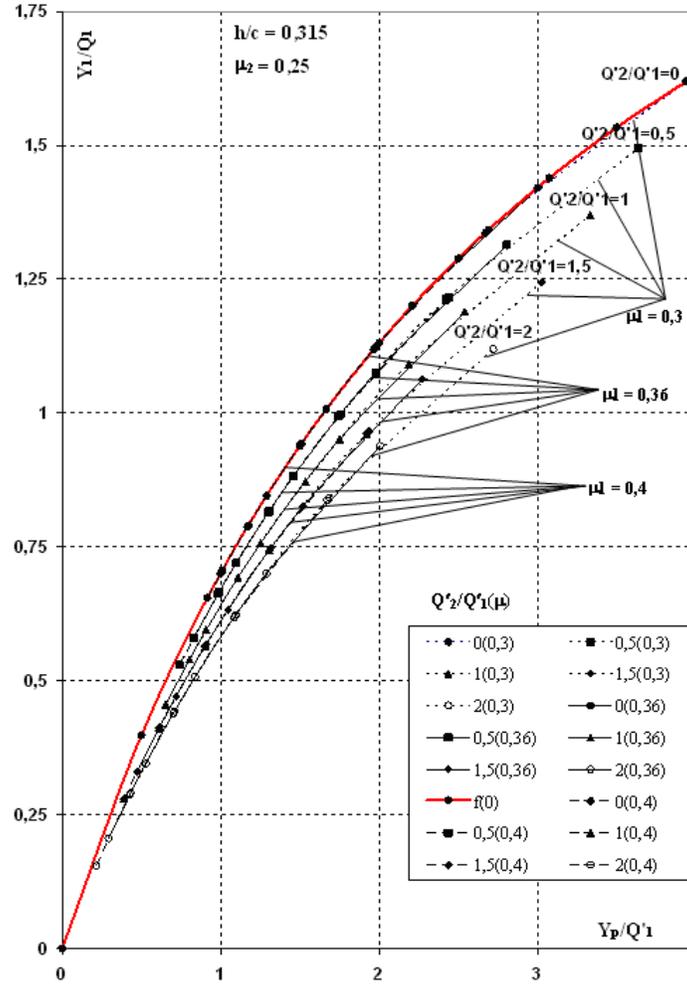


Figure 2. Dependencies between criteria Y_1/Q_1 and Y_p/Q_1 with different values of $\mu_1 (= 0, 0,3; 0,36; 0,4)$ separated according to parameter $Q_2/Q_1 (= 0; 0,5; 1; 1,5; 2)$ for wagon axles of $\phi 920mm$, which are standard according to UIC With values of $\mu_2 = 0,25$ and $h/c = 0,315$ for wagon wheel axles, formula (9) can be specified as follows:

$$\frac{Y_1}{Q_1} = \frac{Y_p/Q_1}{1 + 0,315 \cdot Y_p/Q_1} \left(0,921 - 0,079 \cdot \frac{Q_2}{Q_1} \right) \quad (10)$$

and with parameter varying $Q_2/Q_1 = Q_2/Q_1 (= 0; 0,5; 1; 1,5; 2)$:

$$\frac{Y_1}{Q_1} = \frac{Y_p/Q_1}{1 + 0,315 \cdot Y_p/Q_1} (0,921; 0,882; 0,842; 0,803; 0,764); \quad (11)$$

In case of reverse adaptation from Y_1/Q_1 to Y_p/Q_1 , the following dependency is obtained: Y_1/Q_1 to Y_p/Q_1 , we obtain dependence on the

$$\frac{Y_p}{Q_1} = \frac{Y_1/Q_1}{1 - \mu_2 \cdot \frac{h}{c} - \mu_2 \cdot \frac{h}{c} \cdot \frac{Q_2}{Q_1} - \frac{Y_1}{Q_1} \cdot \frac{h}{c}}, \quad (12)$$

which is in appropriate for practical use under the conditions mentioned in formulas (9) with $Q_2/Q_1 = Q_2/Q_1$.

In cases where the values of wheel load Q_2/Q_1 and Q_2/Q_1 have to be determined, the following formulae shall be used:

$$\frac{Q_2}{Q_1} = \left\{ \frac{Y_p}{Q_1} \left[\frac{h}{c} (1 + \mu_2) - 1 - \frac{\mu_1 \cdot h/c}{\cos \gamma_1 (\cos \gamma_1 + \mu_1 \sin \gamma_1)} \right] + \operatorname{tg} \gamma_1 - \frac{\mu_1}{\cos \gamma_1 (\cos \gamma_1 + \mu_1 \sin \gamma_1)} \right\} \frac{1}{\mu_2} \quad (13)$$

$$\frac{Q_2}{Q_1} = \frac{\operatorname{tg}(\gamma_1 - \rho_1) - Y_1/Q_1}{\operatorname{tg}(\gamma_2 + \rho_2)} \quad (14)$$

The results of the current studies that are appropriate for practical use allow mutual transformation between nominal criterion Y_p/Q_1 and conditional one Y_1/Q_1 or approved one Y/Q according to EN and UIC using three basic methods:

- graphic with a diagram,
- analytical with classical proceeding,
- analytical with software products,

As the analytical methods are those recommended to practice while the graphic one is given rather to illustrate and substantiate the methodology and even to derive basic analytical dependencies.

4. CONCLUSIONS

1. With preserving the basic precondition in Nadal model characterised with forces convergent at one point, a formula of the criterion against derailment is worked out with considering the presence and impact of non-attacking wheel.
2. The so-called “nominal criterion” against derailment is derived based on the nominal forces and its limit value is determined depending on 7 physical values, of which the vertical loads on wheels and the height of distance to frame force Y_p applied to the wheel axle, the so-called “correcting member” containing ratio Q_2/Q_1 , which in fact is inextricably linked to the main part of formula.
3. Due to the adjusted limit value of Nadal criterion and keeping it, there is a possibility to avoid the boundary mode, which is risky for derailment of railway vehicles. On the other hand, the introduction of ratio Q_2/Q_1 , which is examined as a diagnostic parameter, into the system will contribute to its improvement expressed in decrease of the dispersion of results, increase of sensitivity, improvement of the system control, etc.

REFERENCES

- [1] Georgiev N., Integrated and Systemic Approach to Operational Safety of Railway Transport, VTU, Yearbook 6/2015, 2016 (in Bulgarian)
- [2] Valkov R., Railway Infrastructure of the Republic of Bulgaria - Start, Development, State and Perspectives, 140 pp., Sofia, 2012, ISBN 978-954-12-0213-5, "Todor Kableshkov" High School, Sofia, 2012 (in Bulgarian)
- [3] Valkov R., Grozdanov T. Condition and problems in the structural elements of the railway track. , Sp. "Mechanics, transport, communications", issue 3, 2009, ISSN1312-3823, 2009 (in Bulgarian)
- [4] Todorov Y., Valkov R. Modern methods and tools for conducting of complex measurements of the track and the equipment, "Mechanics, transport and communications", issue. 3/3, 2016, ISSN 1312-3823, 2016
- [5] Blokhin, E. P., M. L. Korotenko, I. V. Klimenko, On the Equivalence of Safety Criteria from a Wheel Breaking Down When Using a Guide or Side Force, Science and Transport Progress. Bulletin of the Dnipropetrovsk National University of Railway Transport 2013, 3 (45) ISSN 2307–3489; 74-81
- [6] Karagyozov K., M. Todorova, Analysis of delays of freight and passenger trains on the railway network of Bulgaria, The scientific Journal “MECHANICS TRANSPORT COMMUNICATIONS”, ISSN:1312-3823, 3/2014, paper ID 0962, Sofia, https://mtc-aj.com/library/962_EN.pdf
- [7] Lysyuk, V.S. Causes and the mechanism of the vanishing wheel from the rail. The problem of wear of wheels and rails Publisher: M.: Transport; 2nd Edition, 2002: 215, ISBN: 5-277-02281-3
- [8] Hanneforth, W., W. Fischer. Laufwerke., Transpress VEB Verlag für Verkehrswesen, Berlin 1986; 160
- [9] European Railway Agency (ERA), Study: ‘Impact assessment on the use of derailment detection devices in the EU railway system’, Ref. ERA/REP/03-2009/SAF, 2009
- [10] DIRECTIVE 2004/49/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2004, <https://eur-lex.europa.eu/legal-content/BG/TXT/PDF>
- [11] <http://eradis.era.europa.eu/>
- [12] Nikolov, V. Factors influencing the safety of the railway transport. , "Machines, Technologies, Materials - International Virtual Magazine", issue. 8-9, 2010 (in Bulgarian)
- [13] <http://www.iaja.government.bg>
- [14] <http://www.mtite.government.bg>
- [15] Gavrilovic Branislav, “A Mechatronic Approach for the Detection of Wheel Slip/Slide and Antislip Control of Locomotive with AC Traction Motors”, American Journal of Mechanics and Applications, Vol. 5, No. 6, 2017, pp. 47-52, ISSN: 2376-6115 (Print); ISSN: 2376-6131 (Online).
- [16] Gavrilovic Branislav, Zoran Bundalo: “USAGE OF THE INTERNAL OPTICAL ENCODER FOR THE DETECTION OF WHEEL SLIP/SLIDE AND ANTISLIP CONTROL IN RAILWAY TRACTION SYSTEMSPROCESS”, Proceedings 3rd International Conference „NEW TECHNOLOGIES NT-2016“ Development and Application, pp. 338-347, ISSN 2303-5668

- [17] Gavrilović S. Branislav, Bundalo Zoran, Vukadinović Radisav: „THE RAILWAY VEHICLES OF „SERBIAN RAILWAYS“ WITH WHEEL SLIP CONTROL“, Academic journal: Mechanics Transport Communications, Transport Equipment: Per. No. 0414, VI-1, issue 3, ISSN 1312-3823, 19th International Scientific Conference „Transport 2009“, 2009, Sofia, Bulgaria.
- [18] Nenov N., E. Dimitrov, B. Scrobanski, Basic Principles and Approaches in Modeling and Building of Trains Control System in Motion, Bultrans - 2015, Technical University - Sofia, Faculty of Transportation, 16-18 September 2015, Sozopol, 2015
- [19] Scrobanski B., Development and research of the model of a monitoring system for safety and control in the management of railway vehicles on the railway infrastructure in the Republic of Bulgaria, dissertation, Technical University of Sofia, 2017 (in Bulgarian): http://konkursi-as.tu-sofia.bg/doks/SF_FT/ns/376/avtoreferat.pdf
- [20] Bizic Milan, Petrović Dragan Z, Tomić Miloš C и Djinović Zoran V., Development of method for experimental determination of wheel–rail contact forces and contact point position by using instrumented wheelset, Meas. Sci. Technol. 28 (2017) 075902 (25pp), 2017 IOP Publishing Ltd Printed in the UK
- [21] Nikolov D., N. Nenov, and D. Yosifova, RFID Electronic Sensor System for Rolling Stock Recognition in Motion, 41th International Spring Seminar on Electronics Technology, ISSE 2018, May 16-20, 2018, Zlatibor, Serbia, IEEE Xplore (Impact Factor 9,107), 2018
- [22] Opala M.: Analysis of experimental data in the context of safety against derailment of a railway vehicle, using the energy method, Key Eng. Materials, vol. 518, 2012, pp.16-23
- [23] Nadal M. J.: Theorie de la stabilite des locomotives, Movement de Lacet, Annales des Mines, vol. 10, 1896, pp. 232
- [24] EN 14363-2016, Railway applications - Testing and Simulation for the acceptance of running characteristics of railway vehicles - Running Behaviour and stationary tests, 2016, 196
- [25] 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
- [26] 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, Revised 1993
- [27] Technical Standard for Japanese Railway, available at <http://www.mlit.go.jp/english>
- [28] Elkins, J. and Wu H., Angle of attack and distance-based criteria for flange climb derailment. Vehicle System Dynamics, 33(suppl): 293–305, 2000
- [29] Wu, H., and J. Elkins, Investigation of Wheel Flange Climb Derailment Criteria, Report R-931, Association of American Railroads, Washington, D.C., July 1999
- [30] 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, 2005
- [31] 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
- [32] Shust W., Elkins J., Kalay S., El-Sibaie: Flange climb derailment tests using AAR’s Track Loading Vehicle, Research Report R-910, AAR, December 1997
- [33] Sobaš M.: Stan i doskonalenie kriterijów bezpieczeństwa przed wykolejeniem pojazdów szynowych, Pojazdy Szynowe nr 4, 2005, str. 1-13, Pojazdy Szynowe nr 2, 2006, str. 37-48
- [34] Weinstock, H. Wheel climb derailment criteria for evaluation of rail vehicle safety, In (Ed), Proceedings of ASME Winter Annual Meeting, 84-WA/RT-1, New Orleans, LA, USA, 1984
- [35] Dupont Patrick, Testing the dynamic behaviour of vehicles: Normalisation of test conditions by use of multi linear regressions, Challenge G: An even more competitive and cost efficient railway, IX WCRR, May 22-26, 2011
- [36] Vasilev D.L., Ivanov A.I., Theoretical Mechanics. publ. VTU “T.Kableshkov”, ISBN 978-954-12-0144-2, Sofia, 2008, 2014, pp. 420, (in Bulgarian).
- [37] Ivanov A.I., Structural Dynamics. publ. “Avangard Prima”, ISBN 978-954-323-684-8, Sofia, 2010, pp. 324, (in Bulgarian)
- [38] Ivanov A.I., Three-Dimensional Rigid Body Vibrations. publ. “Avangard Prima”, ISBN 978-619-160-745-7, Sofia, 2017, pp. 192, (in Bulgarian)
- [39] Atmadzhova D., Processes and dependences related to Nadal’s formula IX International Scientific Conference HEAVY MACHINERY 2017, Zlatibor, Serbia, 2017, pp.E7-E16
- [40] Atmadzhova D., Adduction in nominal type of criteria against derailment of railway vehicles. International Scientific Conference on Aeronautics, Automotive and Railway Engineering and Technologies BulTrans-2017, TU-Sofia, Faculty of Transport, pp. 78-83, 2017 (in Bulgarian).